SYSTEMS SCIENCE AND CYBERNETICS

Edited by Francisco Parra-Luna

Volume III

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SYSTEMS SCIENCE AND CYBERNETICS

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Preface

The subject "Systems sciences and cybernetics" is the outcome of the convergence of a number of trends in a larger current of thought devoted to the growing complexity of (primarily social) objects and arising in response to the need for globalized treatment of such objects. This has been magnified by the proliferation and publication of all manner of quantitative scientific data on such objects, advances in the theories on their inter-relations, the enormous computational capacity provided by IT hardware and software and the critical revisiting of subject-object interaction, not to mention the urgent need to control the efficiency of complex systems, where "efficiency" is understood to mean the ability to find a solution to many social problems, including those posed on a planetary scale. The result has been the forging of a new, academically consolidated scientific trend going by the name of Systems Theory and Cybernetics, with a comprehensive, multi-disciplinary focus and therefore apt for understanding realities still regarded to be inescapably chaotic. This subject entry is subdivided into four sections.

The first, an introduction to systemic theories, addresses the historic development of the most commonly used systemic approaches, from new concepts such as the so-called "geometry of thinking" or the systemic treatment of "non-systemic identities" to the taxonomic, entropic, axiological and ethical problems deriving from a general "systemic-cybernetic" conceit. Hence, the focus in this section is on the historic and philosophical aspects of the subject. Moreover, it may be asserted today that, beyond a shadow of a doubt, problems, in particular problems deriving from human interaction but in general any problem regardless of its nature, must be posed from a systemic perspective, for otherwise the obstacles to their solution are insurmountable. Reaching such a perspective requires taking at least the following well-known steps: a) statement of the problem from the determinant variables or phenomena; b) adoption of theoretical models showing the interrelationships among such variables; c) use of the maximum amount of – wherever possible quantitative – information available on each; d) placement of the set of variables in an environment that inevitably pre-determines the problem. That epistemology would explain the substantial development of the systemic-cybernetic approach in recent decades.

The articles in the second section deal in particular with the different methodological approaches developed when confronting real problems, from issues that affect humanity as a whole to minor but specific questions arising in human organizations. Certain sub-themes are discussed by the various authors – always from a didactic vantage –, including: problem discovery and diagnosis and development of the respective critical theory; the design of ad hoc strategies and methodologies; the implementation of both qualitative (soft system methodologies) and formal and quantitative (such as the "General System Problem Solver" or the "axiological-operational" perspective) approaches; cross-disciplinary integration; and suitable methods for broaching psychological, cultural and socio-political dynamisms.

The third section is devoted to cybernetics in the present dual meaning of the term: on the one hand, control of the effectiveness of communication and actions, and on the other, the processes of self-production of knowledge through reflection and the relationship between the observing subject and the observed object when the latter is also observer and the former observed. Known as “second order cybernetics”, this provides an avenue for rethinking the validity of knowledge, such as for instance when viewed through what is known as “bipolar feedback”: processes through which interactions create novelty, complexity and diversity.

Finally, the fourth section centres around artificial and computational intelligence, addressing sub-themes such as “neural networks”, the “simulated annealing” that ranges from statistical thermodynamics to combinatory problem-solving, such as in the explanation of the role of adaptive systems, or when discussing the relationship between biological and computational intelligence.

All the foregoing are complementary aspects, together constituting an indispensable, albeit still insufficient, tool with which to decipher social reality and its numerous problems.

Finally, our utmost gratitude goes to both UNESCO for sponsoring this much needed *Encyclopaedia of Life Support Systems* and the authors who have strived throughout to meet the deadlines and abide by the rules necessary for its successful completion.

Parra Luna.

CYBERNETICS: CYBERNETICS AND THE THEORY OF KNOWLEDGE

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Keywords: Autopoiesis, Cognition, Constructivism, Epistemology, Feedback Mechanisms, Goal-Directed Behavior, Homeostasis, Observation, Operationism, Scientific Models, Self-Regulation, Teleology.

Contents

Summary

After a brief review of the seven articles included under this topic, my own contribution begins with an exposition of salient features of First-Order Cybernetics that opened the way to the development of the Second Order. This is followed by an explanation of the notion of self-regulation and its implications for epistemology in general, for the philosophy of science, and for the common sense view of the world. It will be shown that the idea has historical precedents, but has only recently begun to seep into contemporary disciplines such as anthropology, sociology, psychotherapy, and education.

1. Review of Subject Articles

The seven articles which, with the present one, were collected under the topic 'Cybernetics' reflect the views and interests of individual authors in the field. From its very beginning, this field was developed by the spontaneous collaboration of unconventional thinkers who broke through the established boundaries of their respective disciplines of physics, electrical engineering, neurophysiology, psychology, anthropology, and mathematics. The analyses of phenomena and the novel relations and concepts they came up with were far from uniform, but the collaboration flourished because there was an underlying compatibility of ideas. The individual endeavors were essentially parallel and thus paved a relatively broad pathway into a hitherto untrodden area.

Written half a century after the birth of the discipline, these articles reflect a variety of personal positions and while they duplicate the definitions of some key concepts, the diverge on others. The reader will find a mosaic of ideas, theoretical considerations, and opinions pertaining to areas of the contemporary scene, as diverse as the natural sciences, economy, ecology, business management, social organization, politics, and philosophy. The articles vary in style, but the use of mathematical formalization is rare and none of them require a great deal of scholarly preparation.

1.1. History of Cybernetics

R. Vallée presents a number of historical precursors of cybernetics and discusses some of the founders of the contemporary discipline. He defines special terms, such as 'feedback', 'requisite variety', and the theory of communication. Finally, the article provides a short survey of the influence of cybernetics on other areas and a few projections concerning its future development.

1.2. Existing Cybernetics Foundations

B.M.Vladimirski characterizes cybernetic research as relying on the principles of complex system organization, information transfer, and goal-directed control in the study of living organisms and automatic systems. He provides extensive explanations of all the key concepts of the discipline, including the widely misunderstood concept of 'black box', a rationale for the contention that in a system "the whole is more than the sum of its components", the relativity of explanatory models, the mathematical theory of communication, and he ends with a fervent encouragement for cybernetic research to continue tackling the unwieldy problems human society is running into.

1.3. Second-Order Cybernetics

R. Glanville lays out the differences between 1st-order and 2nd-order cybernetics and gives a lucid account of the conceptual relation that connects them. He compares the step to that from Newton's physics to Einstein's and describes it as the becoming conscious of the discipline. The article also gives a brief account of the personal and intellectual relationships among the scientists who were responsible for the major developments in the field.

1.4. Knowledge and Self-Production Processes in Social Systems

M. Zeleny explores differences between natural and engineering systems. His focus is predominantly on social systems and in particular on free-market economy, kinship networks, and the organization of user networks on the Internet. In all these he examines the application of the concept of autopoiesis and emphasizes the advantages its deliberate practical implementation would bring. He concludes the article by giving several examples of industrial ventures that actually adopted principles of self-generation in their management.

1.5. Cybernetics and the Integration of Knowledge

B. Scott considers cybernetics as a meta-discipline able to inspire scientific research of all kinds and to foster interdisciplinary cooperation and the mutual adaptation of basic conceptual frames, methods of research, and communicatory practices. Beginning with the study of natural systems and observers' initial assumptions, the author distinguishes the classical description of social systems from the approaches that try to understand social phenomena as the manifestations of systems seen as autonomous wholes.

1.6. Cybernetics and Communication

V.U. Degtiar specifies a division between technical and biological objects and, further, between social and non-social systems. He distinguishes man-machine communication from communication among living organisms. Focusing on the second, the author unravels the complexity of communicatory interactions, pointing out the pervasiveness of unconscious aspects that have so far not been taken into account by theoreticians. Stressing the role of the individual and its cognitive resources, he shows some of the obstacles that encumber the discussion of complex problems (also on the Internet). The author comes to several conclusions among which the observation that "the purpose of Homo sapiens is not the quality of its economy but the quality of itself".

1.7. Bipolar Feedback

H. Sabelli presents his concept of bipolar feedback and the application of its mathematical formulation in a variety of areas from physiology to the stock exchange and psychotherapy. The author sees the combination of positive and negative feedback as a source of 'information' that leads to the formation of novel structures. The thesis is presented with a number of mathematical formulations derived from communication theory and complemented by computer simulations that are intended to support its main claim.

2. First-Order Cybernetics

2.1. Historical Roots

The term 'cybernetics' was introduced in the 20th century by Norbert Wiener as the title of his 1948 book. In the subtitle he presented his definition: "Control and communication in the animal and the machine". The word was derived from the Greek 'Kybernetes' which referred to the steersman of a ship and is the etymological root of our word 'governor'. Historians have found prior use of the term in the writings of the French scientist Ampère; and suggestions of control functions similar to those intended by cybernetics could be seen in a paper the famous British scientist Clerk Maxwell wrote in the 19th century.

On the practical side, control devices had been invented long before any cybernetic theory or mathematics was formulated. James Watt's *governor* which, by shutting a valve at a certain rate of revolutions, prevents steam engines from running faster than they should, is the best-known example. In its ingenious design, the rotational speed of the engine itself provides the 'feedback' that reduces the intake of steam. Very much simpler systems, based on a float that 'governs' the level of liquid in a container, have existed ever since the water clocks and the self-filling oil lamps of the 3rd century BC. (For a more detailed history of the discipline-(See *History of Cybernetics*)

2.2. The Notion of Feedback

The basic meaning of 'feedback' is simply this: something that is produced by a machine or organism is led back to modify the process of production. If it increases the output of that process, it is called 'positive feedback'. It is implemented, for example, in the amplifiers of electronic sound technology. If feedback is used to regulate or limit the process that generates it, it is called 'negative'. This second kind if feedback constitutes the core of the control mechanisms that first-order cybernetics is primarily concerned with (see Sabelli's article for elaborations on positive feedback). In the examples mentioned above, negative feedback originates from an inherent physical force. In Watt's governor, for instance, it is a set of rotating weights driven outward by the centrifugal force, that 'sense' the speed of the engine; in oil lamps or water closets there are floats that sink with the consumption of a liquid and 'sense' the near emptiness of a container. Their 'sensing' is of course purely metaphorical. They have no sense organs, but are constructed in such a way that, on reaching a certain position, they respectively close or open a valve by means of a physical connection of levers or chains. (An excellent review of mechanical feedback devices can be found in Otto Mayr's book *The origin of feedback control*.).

In all these gadgets, the feedback is mechanical and does not involve signals or symbolic communication. Nevertheless the more sophisticated among them have features that manifest important theoretical characteristics of cybernetics. For this reason the thermostat was used as the prime explanatory example by the early cyberneticians. In the case of an air conditioning system, the role of the thermostat is to keep the temperature in an enclosed space at the desired level. A human agent sets a specific temperature as reference value, and the thermostat 'senses' the actual temperature by means of a thermometer and has the ability to compare it to the set value. If what it registers is lower than the reference, it activates the heater, if it is higher, it activates the cooling system. Inherent in this function are two principles.

2.3. The Function of Difference

The first of these principles is that whatever action the thermostat initiates, it is not caused by the sensed temperature as such, but by its *difference* relative to the reference value. Consequently any of these actions may cease for two reasons: either because the relevant space has reached a temperature equal to the reference value, or because the reference value has been changed and now equals the temperature the thermostat senses.

It is intuitively convincing that this pattern of acting and reacting provides a useful theoretical model to explain behaviors of living organisms (many instances of it are given in Stanley-Jones' *The kybernetics of natural systems*). The notion of feedback resolves a major problem of stimulus-response theory, namely that whatever is categorized as a stimulus does not always elicit a response. As a rule, also an internal condition has to be considered, and this condition can be seen as discrepancy relative to a 'reference value'. If there is no relevant discrepancy, the perception of the stimulus does not trigger action. Farmers have known this for ever. They say: you can take horses to the well, but you cannot make them drink.

2.4. Self-Regulation and Equilibrium

Besides, the feedback model makes conceptually explicit what Walter Cannon, an important forerunner of cybernetics, called 'self-regulation'. His book, *The wisdom of the body*, is still one of the pillars of biological cybernetics. Indeed, the various types of homeostasis Cannon studied mainly in mammals, all demonstrate the ability to compensate for an environmental perturbation by an internal modification rather than by an action on the environment.

A second principle is not quite so obvious. In order to be a satisfactory regulator, a thermostat must not be too sensitive. It must allow for a reasonable space around the set temperature, so that it does not switch on the heater the moment it senses a temperature just below the set value, and then switch on the cooling system as soon as the temperature has risen above it. In other words, there has to be a range of equilibrium in order to avoid unbearable oscillation.

The realization of this requirement leads to an important shift of focus. Interest is no longer concentrated on isolating *one* external cause of an organism's perturbation, but rather on the conditions that limit its equilibrium, i.e., the constraints within which equilibrium can be maintained. Gregory Bateson applied this idea to the theory of evolution and thus opened a highly productive perspective on the processes of adaptation. As this constituted one of the steps towards second-order cybernetics, we shall return to it in the later context.

2.5. The Domestication of Teleology

Historically, the most important effect of the study of such control mechanisms was the legitimation of the concept of purpose in the domain of science. Notions such as intention and purpose had been declared out of bounds for explanations that wanted to be considered scientific. These notions, it was held, involved something that was logically impossible because they suggested that a goal that lay in the future could influence the course of events in the present. Positing such a paradoxical influence was branded as 'teleology', a pattern of thought invariably associated with the metaphysics of Aristotle. A closer examination shows that this proscription was mistaken on two counts. Re-reading Aristotle, it becomes clear that he separated two kinds of teleology. On the one hand, his metaphysics did, indeed, contain the idea that all development would eventually lead to perfection because it was guided by the blueprint of an ideal world. On the other hand, however, he left no doubt that he saw goal-directed behavior as something eminently practical that involved no mystical assumptions whatever. See *Existing Cybernetics Foundations.*

Aristotle left no doubt about this when, in Book II of his *Physics*, he discussed the fourth of his explanatory principles that translators later termed 'causes'. He called the fourth principle 'final' - not because it was the last, but because it involved the desired end of the activity in question and not, as do the other three, only the initiation or the stuff acted upon. Aristotle's defined the *final* cause by giving the example of someone walking 'for the sake' of his health, and he added the explanation that, in this case, health is the cause of the person's walking about.

He did not think it necessary to state in so many words how people had acquired the belief that walking would be good for them. It was common knowledge that exercise loosens the joints, reduces fat, stimulates the heart and other functions, and could therefore be considered beneficial to one's health. This had long been established by inductive inference from the domain of common experience. It was no different from the knowledge that food will alleviate hunger and that water will quench thirst. It was one of the countless rules of thumb that have proved to be quite reliable and that we use to get rid of discomforts or to attain pleasures. All of them are based on the implementation of an *efficient cause* that has regularly produced the specific desired effect in the past and is therefore expected to produce it in the future. But it is we, who project this effect into the future, not something that exists in the future and affects the present.

2.6. Purpose and Goal-Directed Behavior

Once the analysis of feedback mechanisms presented a model showing how goal-directed behavior could actually work and attain specified goals, the inadequacy of the behaviorist's stimulus-response theory became quite obvious. Although B.F. Skinner in 1977 still persisted in stating that: "The variables of which human behavior is a function lie in the environment", it was apparent that the relation between a thinking organism and its environment was only very rarely explicable in terms of direct causal links. The inner state of the organism, its particular cognitive structures, its individual mental focus and interests, including its goals, had to be taken into account, and the notion of reference values and feedback provided powerful tools in the articulation of this new view.

In retrospect, it becomes apparent that not all the ideas that played a part in the development of the cybernetic paradigm were as new as they seemed. In 1921, Ralph Barton Perry, a philosopher of admirable erudition, published a sequence of articles in an attempt to reconcile the behaviorist approach with the notion of purpose. They are documents of a heroic struggle, and it is fascinating to see how close Perry came at times to the cybernetic concepts of goal-reference and negative feedback. In one of his papers, he said, for example, that an act is performed because its implicit sequel coincides with the incomplete part of some course of action that is at the time dominating the organism. What he did not mention (and presumably did not see) was that the assessment that something is 'incomplete' requires a mental representation of the item in its state of completeness.

Forty years earlier, in his fundamental textbook on psychology, William James had already distinguished two kinds of teleology: that of an agent who deliberately acts to attain a goal; the other, the goal-directedness an observer attributes in order to explain the agent's behavior. This foreshadows the distinction Gordon Pask introduced into cybernetics. Applying Pask's distinction to the thermostat, we can say that its *internal* purpose is the elimination of differences between the set reference value and the temperature it senses, whereas for an *external* observer its purpose is the maintenance of a desired temperature.

To sum up this brief survey: 1st-order cybernetics was primarily concerned with the analysis and engineering implementation of goal-directed behavior. It formulated a viable theory of purposive mechanisms and provided its mathematical formalization. On the practical side, it succeeded in designing and actually constructing a great variety of mechanisms that manifested purposive behavior. The realization of automatic pilots, target-finding missiles, chess-playing computers, and robots capable of guiding their actions by their own perceptions, is ample proof of the power of the cybernetic approach. From a theoretical standpoint, however, the most significant achievement was that the practical success of cybernetic constructs brought with it the rehabilitation of the concept of purpose. This opened the path towards the study of purposive *agents*, the domain of second-order cybernetics. See *Axiological Systems Theory.*

2.7 Communication

While the analysis of feedback was being developed to account for control mechanisms, a no less important theoretical model was worked out as a technical approach to the phenomenon of communication. Communication was the second key term in the title of the book that launched cybernetics, and its problems had been tackled some years earlier by Claude Shannon with some acknowledged contributions from Norbert Wiener. The Mathematical Theory of Communication had an enormous influence in the development of communication technology (the problems of social communication are extensively treated in the article by Degtiar). Far more relevant to the present survey, however, is the conceptual clarification the theory provides for communicatory process in general.

A message can be sent from point A to point B only if there is a medium that allows such transmission. This medium has to be a 'channel' in which pulses of some form of energy can travel. In old-fashioned telegraphy, it was a wire and pulses of electrical energy; in radio and television, it is electromagnetic waves and the modulation of their frequency or amplitude; in speech, it is sound waves and their modulation; and in writing or printing, it is marks on some physical surface that can be taken from one place to another. But these pulses or marks do not carry a message, unless it has been *encoded* in them. For this to happen, three things are necessary. First, the sender must have a code, that is to say, a list that indicates what kind or combination of pulses or marks corresponds to the elements of the message that is to be sent. Second, the receiver of the message must also have such a list in order to *decode* the pulses or marks he receives. Third, if communication is to succeed, the code-lists of the sender and of the receiver must obviously be the same. (Vladimirski gives a more technical explanation of communication theory.)

This last condition was never seen as a problem in technical communication systems, because it was taken for granted that the established code would be distributed to all participants in the system. However, the technical analysis highlights a point that was rarely considered in the study of linguistic communication. Although there are lexica for natural languages, their contents is accessible only to readers who already have a basic vocabulary. Children are not handed a code that displays the connections between words and their meanings - they have to develop it for themselves, largely by trial and error. It is true that the meanings of a number of words can be conveyed to them by parents or care givers, but the bulk of their vocabulary is formed on the basis of subjective experience in the course of interactions with other speakers.

As a result of this inherent looseness in the acquisition of the linguistic code, linguistic messages and texts in general leave a great deal of space for individually divergent interpretations. The realization of this fact had a considerable influence on some of the authors of second-order cybernetics.

3. Second-Order Cybernetics

The difference that separates the two kinds of cybernetics was most succinctly stated by Heinz von Foerster, whose work initiated the new direction. The first order is the cybernetics of observed systems - the second, the cybernetics of observing systems.

Questions about what it means to observe and what kind of knowledge we glean from observation, were raised already by the pre-Socratics at the very beginning of recorded Western philosophy. In the course of this history, innumerable theories of knowledge were proposed, ranging between two extremes. On the one side there is naive realism which is based on the assumption that what we come to know must be a more or less 'true' representation of an independently existing reality. On the other side, there is the form of subjective idealism that is called solipsism and holds that there is no reality beyond the human mind. At the realist end of this axis looms the problem of how our knowledge could ever be *demonstrated* to be true relative to a reality posited to be independent of its observers; at the other, there is the no less daunting puzzle why so many things concocted in the domain of our ideas turn out to be patently false in the world which we actually experience.

3.1. The Epistemological Problem

Scattered throughout the history of philosophy there are thinkers who came to see that it was impossible to find a rationally tenable position anywhere on the established axis. Whatever was proposed, contained one or more elements of either one of the two extremes and could therefore be demolished by well-established arguments. There seemed to be no way to counter the sceptics' solidly founded contention that true knowledge of either the world or the mind was impossible. Consequently the nature of what we consider to be justified beliefs remained a troublesome problem.

In the sciences, problems that resist solution for a long time, are usually solved in the end by the drastic modification of one or more concepts that until then were unquestioningly taken for granted. The conceptual changes were sometimes dramatic and their proponents faced fierce resistance before the established leaders of their respective field gave in (or died) and a new way of thinking gradually became general. The shift from the geocentric to the heliocentric theory of the planetary system is probably the most obvious among the historical examples. In general it was either the accumulation of empirical evidence or the wider applicability or simplicity, that gave the new conceptualization the winning edge. Suggested before the Second World War by the Polish author Ludwick Fleck, this theory of scientific procedure and change was elaborated and presented by Thomas Kuhn, in his book *The structure of scientific revolutions* that became the scientific best-seller of the post-war period.

Philosophy, and epistemology in particular, do not show this pattern. The unsolved problems in these disciplines are largely the same as they were two and a half millennia ago, and so are the concepts involved in the problems' formulation. One of these is the very concept of knowledge. It has been, and generally still is, taken for granted that what we want to call knowledge must in some way correspond to a reality that lies beyond our experiential interface. Like the notion that the earth must be at the center of the universe, it is an idea that is difficult to give up. Yet no one seemed to be able either to demonstrate such correspondence with an independent reality, or alternatively, to give a convincing account of how, without it, we could come to have all the knowledge that we confidently trust when we make decisions about our actions.

3.2. A New Theory of Cognition

Some years before cybernetics was born as a discipline, Jean Piaget formulated a principle of self-organization as: "The mind organizes the world by organizing itself" in his 1937 book on the child's construction of reality. In his theory, this autonomous process of organization forms the core of the capability of producing knowledge and is the highest form of adaptation. He took the concept of adaptation out of the context of evolution, where it does not involve an activity, but concerns the biological capacity to survive within the constraints of the physical environment; and he transposed it into the cognitive domain, where it concerns the active striving for and maintenance of equilibrium among concepts, schemes of action, and in the generation of knowledge as a whole.

Talcott Parsons was among the first to remark on the relation between Piaget's theory, Cannon's concept of homeostasis, and the revolutionary notion of self-regulation. But it was Gregory Bateson's analysis of the process of adaptation that allowed us to see clearly the conceptual connection between Piaget's theory of cognitive equilibrium and cybernetics. (For a more extensive survey of the researchers involved in the development of the second order, see Glanville's article.)

"Causal explanation", Bateson wrote in his seminal article on biological evolution, "is usually positive. We say that billiard ball B moved in such and such a direction because billiard ball A hit it at such and such an angle. In contrast to this, cybernetic explanation is always negative. We consider what alternative possibilities could conceivably have occurred and then ask why many of the alternatives were not followed, so that the particular event was one of those few which could in fact occur. The classical example of this type of explanation is the theory of evolution under natural selection. According to this theory, those organisms which were not both physiologically and environmentally viable could not possibly have lived to reproduce. Therefore, evolution always followed the pathways of viability. As Lewis Carroll has pointed out, the theory explains quite satisfactorily why there are no bread-and-butter-flies today. In cybernetic language, the course of events is said to be subject to *restraints*, and it is assumed that, apart from such restraints, the pathways of change would be governed only by equality of probability. In fact, the 'restraints' upon which cybernetic explanation depends can in all cases be regarded as factors which determine inequality of probability".

In the theory of evolution, the biological living space of each organism is hemmed in by the limits entailed by its physiological make-up and by the obstacles presented by its environment. Both these are given conditions over which neither the individual nor the species has control. In contrast, in Piaget's theory of cognition, a relative, labile equilibrium is possible only in the space generated by the active avoidance of, or continual compensation for, perturbations. The conceptual difference between the two essentially parallel theories resides in the source of the restraints. On the biological level the factors that limit survival are in no way determined by the organism itself. On the cognitive level, however, perturbations that impede equilibrium spring from the mutual incompatibility of goals the organism has chosen and/or of the means used to attain them.

3.3. The Construction of Knowledge

In this view, cognitive agents themselves are clearly determining factors in the generation of knowledge. For if the goal is conceptual equilibrium, only the conceivers themselves can determine when it is reached and when not.

There is yet another quite different consideration that has brought the role of the cognitive agent to the fore. In his book, *Cybernetics - or control and communication in the animal and the machine*, Norbert Wiener wrote: "All the great successes in precise science have been made in fields where there is a certain high degree of isolation of the phenomenon from the observer". In Astronomy, he goes on to explain, the scale is "enormous", in atomic physics "unspeakably minute" compared to the scale on which we live. In both cases, he says, "we achieve a sufficiently loose coupling with the phenomena we are studying to give a massive total account". At the end of the passage, however, he warns that "the coupling may not be loose enough for us to be able to ignore it altogether".

Second-Order Cybernetics could be characterized partially by saying that it originated from the doubt expressed in Wiener's warning. The relationship between observers and what they observe became its primary object of study. This study, clearly, did not have to begin from scratch. Beginning with the famous statement "Man is the measure of all things", made by Protagoras in the 5th century B.C., there is a chain of records indicating that some thinkers had come to realize that the observer plays an active part in the process of observation and that anything he observes bears his mark. But they have had relatively little influence on the philosophical tradition.

Even the clear statement that Immanuel Kant made in the Introduction to his *Critique of pure reason,* namely that "reason can understand only what she herself has brought forth according to her design" did not greatly shake the general belief that scientists succeed in unveiling the mysteries of the universe.

3.4. Rational Models and the Role of the Observer

Second-order cybernetics is the only Western discipline that has fully accepted this view and subscribes without reservation to the general description of the scientist which Albert Einstein and Leopold Infeld provided by means of the famous metaphor of the man and the watch in their *Introduction to relativity*.

"Physical concepts are free creations of the human mind, and are not, however it may seem, uniquely determined by the external world. In our endeavor to understand reality we are somewhat like a man trying to understand the mechanism of a closed watch. He sees the face and the moving hands, even hears its ticking, but he has no way of opening the case. If he is ingenious he may form some picture of a mechanism which could be responsible for all the things he observes, but he may never be quite sure his picture is the only one which could explain his observations. He will never be able to compare his picture with the real mechanism and he cannot even imagine the possibility or the meaning of such a comparison."

This metaphor brings home the fact that the real world is unknowable or, as cyberneticists came to say, a 'black box' (for a full explanation of this term, see Vladimirski's article). The 20th-century revolutions in physics, especially that provoked by quantum theory, prompted all their foremost exponents to declare, in one way or another, that the knowledge they had gathered concerns the organization of experience rather than the objective structure of an independent reality. But the attitude in most physics departments and of the writers of textbooks still tends to be that of realists. See *Second-order Cybernetics (Glanville).*

3.5. Operational Definitions

Another development that, in retrospect, could have accentuated the role of the observer, was that of 'operational definitions' by the physicist Percy Bridgman. He succinctly characterized the ideal attitude of the researcher in his 1936 treatise on *The structure of physical theory*: "It is the task of theoretical physics to compress all experimental knowledge into an understandable point of view; the theorist can never foresee what the experimenter will find when his range is extended to include fields at present inaccessible, so that he must always regard his last and most successful theory as a structure of limited validity, always subject to the necessity for radical alteration when extended to include such new experimental facts as may be later discovered."

Bridgman formed the operationist idea in the context of Einstein's theory of relativity by an examination of the concept of simultaneity. He explained that the germ of the theory had been the examination of what we do when we compare the times indicated by clocks in different places. Einstein's revolutionary recognition was that the property of two events which hitherto had been unthinkingly called simultaneity involves a complicated sequence of physical operations which cannot be uniquely specified unless we specify who it is that is reading the clocks.

Every observer, be he or she reading a clock, looking through a telescope, or simply watching an event, has a specific *position*, not only in the spatial sense. Like the optical instruments scientists use, all observers have their own observational characteristics and their specific way of seeing. They also have a 'point of view' that determines the concepts with which they grasp what they observe and how they formulate it when they want to communicate it to others. The 'coupling' Wiener spoke of, between the agent and the object of observation, can therefore not be disregarded.

3.6. Several Parallel Developments

Once interest was focused on the cognitive processes involved in observation, cyberneticians found themselves facing the problems that had bedeviled epistemologists during the entire course of history. The protagonists of the new discipline, however, had the advantage of a highly technical background. The successful engineering of purposive devices that manifested a practical solution of the puzzle of teleology, helped to generate the confidence to break with other traditional philosophical assumptions. The most fundamental of these dogmatic fixtures was the belief that human knowledge ought to mirror a timeless, independent reality.

If the Piagetian principle that the mind organizes itself is taken as a working hypothesis, it becomes very clear that the primary purpose of knowledge is not the representation of an external world but rather the establishment of ways of thinking and ways of acting that serve the purposes the knower has formed in the world of his or her experience. This realization led to different but essentially parallel developments within the framework of second-order cybernetics.

For some of the pioneers, George Spencer Brown's book *Laws of form* provided additional conceptual foundation. The 'calculus of distinctions' presented in this book can be seen as the most elementary basis of all logical thinking. According to Spencer Brown, the act of making a distinction is the first step in any sequence of rational thoughts. This offers an ideally simple starting-point for conceptual construction and, indeed, led the author himself to the striking statement: "our understanding of [...] a universe comes not from discovering its present appearance, but in remembering what we originally did to bring it about".

Linked by the common goal of a constructivist epistemology, individual cyberneticians went their own way in their struggle with the problems of cognition. In the narrow frame of this survey only the three relatively complete theoretical models can be acknowledged.

3.6.1. Radical Constructivism

Heinz von Foerster started from the fundamental insight that there can be no observation without an observer. What we call 'real', therefore, is always rooted in an observer. In his seminal 1973 article *On constructing a reality*, Heinz von Foerster explained his use of 'a' in 'a reality':

The indefinite article, he says there, implies the ridiculous notion of other realities besides 'the' only one that we cherished as our Environment. "There is a deep hiatus that separates the 'The'-school-of-thought from the 'A'-school-of-thought in which respectively the distinct concepts of 'confirmation' and 'correlation' are taken as explanatory paradigms for perception. The 'The-School': My sensation of touch is *confirmation* for my visual sensation that there is a table. The 'A-School': My sensation of touch in *correlation* with my visual sensation generate an experience which I may describe by 'here is a table' I reject the THE-position on epistemological grounds, for in this way the whole Problem of Cognition is safely put away in one's own cognitive blind spot and its absence can no longer be seen."

The statement that it is the cognitive agent's active correlation of sensory impressions that creates the notion of objects would be somewhat dubious if it were taken by itself. But von Foerster supports it by citing the 'Principle of undifferentiated coding', formulated by Johannes Mueller before the middle of the 19th century and confirmed by neurophysiologists ever since. The principle summarizes the finding that the neural signals sent from an organism's sensory 'receptors' to the brain are qualitatively all the same and differ only in intensity. In von Foerster's formulation, "the response of a nerve cell does *not* encode the physical nature of the agents that causes its responses. Encoded is only *how much* at this point of the body, but not *what*". This well-established empirical finding presents a serious stumbling block for all realist theories of knowledge.

The epistemological position of radical constructivism is primarily based on the logical consideration that observers necessarily conceptualize what they observe in terms of concepts that are of their own making (as Kant said, according to reason's own design); but the fact that the 'data' of vision, hearing, touch, smell, and taste are from the neurophysiologist's point of view all indistinguishable is a welcome empirical corroboration of the perceiver's autonomous constructive activity.

The constructivist theory of knowing, one of the cornerstones of second-order cybernetics, can be briefly summarized in four principles:

- Knowledge is the result of a cognitive agent's active construction.
- Its purpose is not the representation of an external reality, but the generation and maintenance of the organism's equilibrium.
- The value of knowledge cannot be tested by comparison with such an independent reality but must be established by its viability in the world of experience.

3.6.2. The Theory of Autopoiesis

Humberto Maturana developed his theory of cognition as a biologist involved in the study of perception. Investigating vision in frogs and color vision in pigeons and primates, he came to the conclusion that responses in these organisms were not triggered by specific external stimuli but by the co-occurrence of neural events that showed no one-to-one relation with conditions or events in their environment. In experiments done by Lettvin, Maturana, McCulloch, and Pitts in 1959, a frog, for instance, would respond with its 'bug-catching' behavior whenever three or four neural signals created a specific pattern in its brain, irrespective of the fact that, from an observer's point of view, what caused the individual signals in the frog's visual organ may have nothing to do with a bug that could be eaten by the frog. The 'what' that caused the response was far from fully determined, and this finding required a radical revision of the generally accepted theory of more or less direct perception.

A partial conceptual skeleton of the 'autopoietic' model of cognition, which Maturana worked out during the subsequent decade, can be summarized by the following statements:

(a) Whatever is said, is said by an observer to another observer who may be the speaker him- or herself.
(b) Cognition as a process is constitutively linked to the organization and structure of the cognizing agent.
(c) Autopoietic systems are closed homeostatic systems without input or output.
(d) The changes of state through which an autopoietic system goes while compensating for perturbations can be seen by an observer, for whom the system is in the context of an environment, as the system's actions upon the environment.

From this perspective, it becomes clear that the observer should remain aware of the fact that the observed organism and the environment in which it is being seen are parts of the observer's experiential field and therefore not an objective reality.

When Maturana published statement (a) for the first time in 1970, it immediately seemed to be a perfectly obvious statement to his readers; but a look at the histories of philosophy and science shows that the quest for descriptions of the world that could be considered 'objective'. in the sense that they are *not* dependent on the characteristics of the observer, was never given up.

Statement (b) can easily be translated into Piagetian terms by saying that what a cognitive organism comes to know is necessarily shaped by the concepts it has constructed.

The term 'closure' in statement (c) is intended to indicate that the equilibrium of the autopoietic system may be perturbed from the outside, but there is no input or output of 'information'; its actions are in the service of its homeostasis.

Statement (d) speaks for itself. It is an application of statement (a) in that it makes explicit that whatever is conceptualized and said about an observed system is an observer's description of something within that observer's experiential field, not a description of a world as such.

Maturana's autopoietic model is a highly complex and comprehensive theoretical edifice. The four points listed here may serve to render an idea of its general direction but they cannot convey the variety of original ideas that the edifice contains. The many applications that have been developed from it in areas as diverse as family therapy, immunology, and management science are testimony to its inherent richness. (The article by Zeleny is a good example of an independent application.) See also *The Dynamics of Social and Cultural Change.*

3.6.3. The Italian Operational School

One of the first centers of cybernetics in Europe focused from the very beginning on the problems of conceptualization and its role in the semantics of linguistic communication.

Traditional semantics has always been limited to using words in order to define the meaning of words. For the rest, it relied on the theory of reference, based on the belief that words *refer* to things in an external, speaker-independent world. Ferdinand de Saussure, the Swiss founder of modern linguistics, had already shown at the beginning of the 20th century that the semantic linkage was not between words and things, but between the concepts of words and the concepts of things. Both the signs and what they signified were wholly within the experiential world. The illusion of external reference sprang from the fact that meaning could to a large extent be considered *intersubjective.* Concepts were explained as abstractions the speakers of a language learned to make in the course of their common experience (see 1.7, above). Piaget called this process 'empirical abstraction' where it could be shown to originate from sensory experiences; and he added the level of 'reflective abstractions' which derive from mental operations. The idea that mental operations are a source of knowledge goes back to John Locke. But neither Locke nor Piaget nor Guy Cellérier, who wrote about the connection between Piaget's theory and cybernertics, further analyzed the mechanisms of abstraction that might yield results that could then be named by words. This analysis was undertaken by Silvio Ceccato but has remained virtually unknown because it was published only in Italian.

Silvio Ceccato's main objective was "the mechanization of the mind", by which he intended the design of a model that could carry out mental operations. Early on, he had stumbled on Bridgman's idea of operational definitions and it determined the course of his work. If the meaning of words was conceptual, a valid semantic analysis required the specification of the medium out of which concepts could be made *before* they were associated with words. This position became the basis of several projects of language analysis by computer in the 1960s. As material of the conceptual constructs Ceccato posited an active process of attention. Unlike the general notion that attention functions as a kind of 'spotlight' that illuminates objects, he saw it as an oscillatory process producing regular pulses. These pulses could either focus on other signals in the neural network or remain unfocused to mark intervals and distinctions. This attentional activity provided a mechanism for the composition of conceptual structures.

His team at the Milan Center of Cybernetics worked extensively on the minute analysis of mental operations that constitute the meaning of words. Like any effort to produce a comprehensive lexicon, it was a gigantic project. When funds dried up, the team dispersed in the mid 1960s. Giuseppe Vaccarino, who carried on single-handed for forty years, has now brought the work to a conclusion with several volumes on the conceptual foundations of the Italian language. Ceccato's theory of 'operational awareness' is kept alive, applied, and further developed in the electronic age by Felice Accame and the Società di Cultura Metodologico-Operativa which he directs (www.dellacosta.com/methodologia)

4. Applications of Cybernetic Principles

The idea that the experiencing subject shapes its experience according to its own ways of perceiving, conceiving and feeling was implicit in the writings of many authors long before cybernetics proposed cognitive self-organization. But it remained a marginal idea and never became an insight that determined general philosophical views. Recent philosophers, such as Nelson Goodman and Richard Rorty, whose epistemological views are partially compatible with the theory of knowledge developed in second-order cybernetics, use only arguments generated within the tradition of their field and do not mention the parallels to this other contemporary area of research.

In a few disciplines the situation is different. The cybernetic theory of knowing has begun to play a noticeable role in anthropology, sociology, psychotherapy, and, most importantly, in education. What follows is no more than a sampling of conceptual parallels.

4.1. Anthropology and Sociology

Gregory Bateson began his career as an anthropologist with a thorough preparation in biology. His cybernetic analysis of the theory of evolution and his clarification of the concept of adaptation, at first a by-product of his studies of natives in New Guinea, led to the notion of self-organization and his cybernetic view of knowledge. Owing to his work and that of others such as Harold Garfinkel and Clifford Geertz, the perspective of anthropologists was slowly shifted. The earlier attitude, founded on the European notion of scientific objectivity gave way to the realization that viable knowledge of other cultures could be attained only by a participatory understanding of their conceptual and social structures. (For a somewhat different elaboration of this theme, see the article by Scott.)

This development was in keeping with the cybernetic maxims that there are no observations without an observer and that the observer's explanation of the observed is at best a model that proves viable in the experience of others. Geertz formulated the new attitude in his book *The interpretation of cultures*:

> We (anthropologists) begin with our own interpretations of what our informants are up to, or think they are up to, and then systematize those (...) In short, anthropological writings are themselves interpretations, and second and third order ones to boot. They are, thus, fictions; fictions, in the sense that they are 'something made', 'something fashioned' - not that they are false, unfactual, or merely 'as if' thought experiments. Cultural analysis is (or should be) guessing at meanings, assessing the guesses, and drawing explanatory conclusions from the better guesses, not discovering the Continent of Meaning and mapping out its bodiless landscape.

The influence of cybernetics on sociology has been far more direct. Niklas Luhmann, whose work has become quite familiar beyond the German-speaking sphere, adopted and adapted Maturana's autopoiesis and added an intricate model of communication in his construction of a complex and comprehensive theory of society and societal manifestations. His personal interactions with both Maturana and Heinz von Foerster brought out some disagreements about his use of their ideas. Maturana objected that societies could not be considered autopoietic systems because one could not ascribe to them the biological structure and organization which, from his point of view, is indispensable for autopoiesis. Von Foerster, who had contributed much to the clarification of the concept of information, could not accept the notion of communication as a reified element in Luhmann's theoretical edifice. Nevertheless Luhmann's work on *Social systems* constitutes a major, albeit idiosyncratic, application of second-order cybernetics.

4.2. Psychotherapy

Considerations not unlike Wiener's admonition that the relation between observers and what they observe cannot be altogether disregarded, have wrought a significant change in the theory and practice of psychotherapy. Traditionally, it was held that there is a clear, demonstrable difference between the sane and the insane, and that mental insanity could therefore be detected and objectively characterized with relative ease. Empirical studies, by Rosenhahn and others, however, have shown that an objective observation of behaviors and their categorization as 'abnormal' is very often problematic. A large-scale investigation of what happened to 'normal' people who were committed to psychiatric hospitals, shook the discipline to its foundations. Among other things, the study made two points appallingly clear: (a) The observation of *behaviors* always involves a particular interpretation of what are considered empirical facts; (b) both the facts and their interpretation are to a large extent determined by the observer's expectations. Thus, normal reactions of a pseudopatient were interpreted as symptoms of schizophrenia by the hospital staff, for no other reason than that the person had been categorized as a schizophrenic when he or she was being admitted.

As a corollary of the realization that observations could not be considered to be independent of the observer's concepts, theories, and contextual assumptions, the conceptual fictions of patients were no longer seen as totally erratic. Instead, it was assumed that they had their own, albeit 'abnormal' logic and systematicity and that at least in some cases therapy had a better chance if it explored the patient's ways of thinking. This approach, of course, contrasts sharply with the common practice of categorizing patients as mentally ill and then treating them pharmaceutically.

Gregory Bateson and Paul Watzlawick introduced the cybernetic way of thinking into Psychotherapy and the development of different therapeutic methodologies on the basis of second-order principles is still going on. To give an instance, constructivism and Maturana's autopoietic model in particular had a considerable influence in the area of family therapy. Its general approach has been guided by the notion that each member of a family constructs his or her own 'reality' of the family, and that the problems of, and conflicts among, the individuals often spring from the incompatibility of their constructions.

4.3. Education

The cognitive psychology of Jean Piaget had a first bout of influence on the practice of teaching some sixty years ago. His specification of stages of development was picked up by designers of curricula and the notion of the role of biological maturation in the ontogeny of mental development became a kind of dogma for educators and educational researchers. The epistemological core of Piaget's theory, however, was largely disregarded. Not until around 1970 did a number of researchers focus on the idea of self-regulation. By then Piaget himself had become aware of the affinity of his theory and basic concepts of second-order cybernetics. Above all, they shared the principle that whatever we call knowledge has to be actively constructed by the knowing subject.

From then on, this principle of self-organization gained some attention among educators. By now, it has a firm foothold in the areas of mathematics and science education. An extensive literature concerning the individual and social construction of knowledge has been produced and there is considerable evidence that its practical applications are successful, but it is still far from being universally accepted.

Among the points stressed by advocates of constructivism are the following:

- If knowledge consists of conceptual structures learners have to form in their own heads, verbal communication (by teachers' speech or textbooks) does not guarantee a positive result. What is required is *thought,* i.e. reflection on both practical experiences and whatever teachers and books try to communicate.
- Two excellent ways for teachers to foster students' reflection are the imposition of collaboration with others and the persistent demand that students verbalize their thinking in their attempts to solve a problem ('Team problem-solving').
- The implementation of the constructivist approach requires two things of teachers: they have to credit students with the ability to think and they have to provide the students with opportunities to discover that they are able to solve problems without the teacher providing a ready-made solution.
- And, most important perhaps, the insight that linguistic communication cannot replace students' active abstraction of knowledge from their own experiences.

These four points are sufficient to indicate the need of a radical change of educational attitude: namely the concession of a great deal of autonomy to the student in order to develop their own capacity for thinking and learning.

A serious argument against such a change is that it would require tests that are very different from the ones given to students now. This is indeed a problem. Testing for *understanding* is far more difficult than testing for the correct repetition of verbal statements heard from the teacher or read in a textbook. On the other hand, there is sufficient evidence by now, that the *motivation* to learn grows by itself once students realize that learning is not a passive but an *active* process and that the ability to solve problems *by one's own thinking* yields satisfactions that are at least as enjoyable as winning a game.

5. Conclusion

First-order cybernetics originated in 1948 with Norbert Wiener's publication of his book that had the new word as its title. It was baptized as an independent discipline when the prestigious Josiah Macy Foundation decided to devote meetings to the new area of research during the years that followed. Before it was given its name, it had already started and now continued at a growing pace to revolutionize technology by introducing self-regulating mechanisms that could fly planes, guide the actions of robots, and enabled computers to prove theorems and play chess. Today nearly all the machines that serve us in the conduct of our daily lives contain cybernetic devices - from the braking systems of the cars we drive and the traffic lights that control our driving, to the networks of electric power and the photographic cameras we use.

Hand in hand with the technological innovations went two conceptual revolutions. On the one hand, the successful analysis of feedback mechanisms made the notions of purpose and goal-directed behavior respectable elements in scientific explanation; on the other, the theory of communication substantiated the old suspicion that language by itself was not a vehicle for the transportation of knowledge; it could stimulate conceptual construction, but it could not carry concepts from one head to another. From these premises developed second-order cybernetics which, by means of the concept of self-regulation, was able to propose a novel approach to the age-old problems of the theory of knowledge. From this new perspective, human knowledge is defined as the repertoire of ways of thinking and rules of action that are found to be successful in the domain of experience. Thus, *viability* is put in the place of ontological truth. The momentous change is justified by the fact that we gather our rational knowledge from experience and the only way we have of testing it is again through experience. This in no way diminishes the role of that other kind of knowledge which the religious and the mystics of all ages claim to possess on the basis of revelation or intuition. That knowledge, however, owing to its origin, is beyond the purview of rational analysis.

The epistemological proposal of second-order cybernetics is still viewed with suspicion by traditional philosophers and it will take time to overcome their resistance. One reason why the notions of cognitive self-regulation and that of experiential viability, instead of ontological truth, are difficult to accept may be that it is easier to put up with the contention that one's solution to a problem may be wrong, than with the idea that *no* solution will ever be the only 'true' one.

Nevertheless, the focusing on self-regulation in an area of possibilities within constraints has led to considerations that seem eminently appropriate at the present moment in human history. In one of the papers that launched his notion of a second-order cybernetics, Heinz von Foerster formulated a guide-line for society by referring to the rehabilitated concept of purpose. His admonition, made a quarter of a century ago in *The cybernetics of cybernetics*, seems no less pertinent today:

'Social cybernetics must be a second-order cybernetics, in order that the observer who enters the system shall be allowed to stipulate his own purpose: he is autonomous. If we fail to do so, somebody else will determine a purpose for us. Moreover, if we fail to do so, we shall provide the excuse for those who want to transfer the responsibility for their own actions to somebody else: 'I am not responsible for my actions; I just obey orders'. Finally, if we fail to recognize autonomy of each, we may turn into a society that attempts to honor commitments and forgets about its responsibility.'

Glossary

Adaptation:	serves the ability to survive, reproduce, or maintain equilibrium within limiting constraints.
Cognition:	the mental faculty of generating and compiling knowledge.
Control:	to keep a process or quantity within limiting bounds.
Ontology:	the study of what is presumed to exist irrespective of human observers.
Perturbation:	anything that upsets an equilibrium.
Realism:	the doctrine based on the belief that it is possible to obtain

"objective" knowledge of a world underlying experience.

Teleology: the use of the concept of purpose in the explanation of phenomena.

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Biographical Sketch

Ernst von Glasersfeld was born in Munich, 1917, of Austrian parents, and grew up in Northern Italy and Switzerland. Briefly studied mathematics in Zürich and Vienna and survived the 2nd World War as farmer in Ireland. Returned to Italy in 1946, worked as journalist, and collaborated until 1961 in Ceccato's Scuola Operativa Italiana (language analysis and machine translation). From 1962 principal investigator of US-sponsored research project in computational linguistics. From 1970, he taught cognitive psychology at the University of Georgia, USA. Professor Emeritus, 1987. - At present Research Associate at Scientific Reasoning Research Institute, University of Massachusetts.

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Papers: more than 240 since 1960.

Honors:
University of Georgia Research Medal, 1983.
Christ Janer Award for Creative Research, 1984 (jointly with L.P.Steffe). Chairman, Third Gordon Research Conference on Cybernetics, Oxnard, CA, January 1988.
Warren McCulloch Memorial Award (American Society for Cybernetics), 1991.
Trustee, American Society for Ctbernetics.
Honorary Member, Austrian Society for Cybernetics, 1996. Member, International Board of Consultants, Archives Jean Piaget, Geneva, 1996.
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HISTORY OF CYBERNETICS

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Keywords: Autopoiesis, cybernetics, entropy, feedback, information, noise, observation, variety.

Contents

Summary

The most important initiator of cybernetics was Norbert Wiener (l894–1964) with his book "Cybernetics or Control and Communication in the Animal and the Machine". The contribution of Warren S. McCulloch (1898–1969) may be compared to that of Wiener. Cybernetics has also had precursors such as A. M. Ampère who introduced the word cybernétique as well as B. Trentowski who did the same in Polish. H. Schmidt, S. Odobleja in the 1930s, and P. Postelnicu in the early 1940s recognized the general importance of the idea of negative feedback.

The basic concepts of cybernetics are negative feedback and information. A famous example of negative feedback is given by Watt's governor, the purpose of which is to maintain the speed of the wheel of a steam engine, at a given value, despite perturbations. The theory of information, mainly due to Claude E. Shannon, gives a measure of the unexpectedness of a message carried by a signal.

Other traits of cybernetics must be noted, such as the "principle of requisite variety" introduced by W. Ross Ashby. It tells that to efficiently resist a given level of variety of aggressions it is necessary to dispose of a comparable level of variety of opposite actions. "Second order cybernetics" emphasizes the role of observation played by a cybernetic device which has to perceive in order to adjust its behavior to its aims.

Other theories have connections with cybernetics. The most important of them are: systems theory introduced by L. von Bertalanffy, the synergetics of H. Haken, and the study of dissipative structures promoted by I. Prigogine.

The program proposed by Wiener, not yet fulfilled, concerned many fields of investigation in the worlds of the artificial, of human sciences, and in the symbiosis of man and machine. (See chapter *Cybernetics and the Theory of Knowledge*)

1. Origins of Cybernetics

1.1 Contemporary Initiators

Cybernetics began properly with the publication, in 1948, of a book by Norbert Wiener entitled "Cybernetics or Control and Communication in the Animal and the Machine". The word cybernetics had been chosen by Wiener, in agreement with other colleagues, from the Ancient Greek *kubernetike*, or the art of steering. Another initiator, almost as important as Wiener, is Warren S. McCulloch who published, in 1943, in collaboration with N. Pitts, an article on logics and the nervous system. The directions of approach of Wiener and McCulloch were different—Wiener saw Leibniz as the historical patron of cybernetics, whereas McCulloch was inspired by Descartes. Wiener's preference was due to Leibniz's interest in the construction of a calculating machine, and his attempt to build up a general calculus of logics (calculus ratiocinator). Contrastingly, McCulloch observed that Descartes, in his treatise on man, had introduced negative feedback in his description of how an individual escapes the inconvenience of a fire close to his foot. Incidentally, this would seem to show that it is wrong to see Descartes as a promoter of a reductionism based upon decomposition into material parts. Here the kind of reflex arc seen by Descartes is of a holistic conception. In fact Descartes only recommends decomposition of logical difficulties into parts.

It may be of interest to note that J. von Neumann also had contact with Wiener and McCulloch, mainly in a group sponsored by the Macy Foundation called the Teleological Society, or informally the "Cybernetic Club", to which H. von Förster also contributed. Other associations also devoted to cybernetics included the Cercle d'Etudes Cybernétiques in France, and the Ratio Club in Great Britain.

Other initiators to be covered in more detail below are Claude E. Shannon and William Ross Ashby. The importance of Shannon, for his essential contribution to communication theory, was recognized by Wiener himself. The eminent role of Ashby had more to do with control seen from the point of view of "requisite variety". Other contemporary initiators were P. Vendryès, with his early theory of autonomy, S. Odobleja, and P. Postelnicu who understood the general role of retroaction. H. Schmidt also deserves special mention for his introduction of a "general science of regulation loops", as does J. Lafitte who recognized the interest of what he called "reflex machines".

1.2 Past Contributors

The importance of older influences must not be overestimated, but Plato, A. M. Ampère, S. Trentowski, and C. Bernard should definitely be mentioned. Plato, in "The Republic" and "Gorgias", used the metaphor of steering (*kubernetike*) to present the art of government. A. M. Ampère, in the second volume of his essay on the philosophy of science, introduced the word *cybernétique* with the same purpose as Plato. S. Trentowski, in a book on a management, proposed *kibernetiki* as a new Polish word. C. Bernard, in his introduction to experimental medicine, emphasized the role of regulations in the equilibrium of the body, an idea which W. B. Cannon made famous with the concept of homeostasis, also used by P. Vendryès. More precisely, Bernard emphasized the importance of the constancy of the “milieu intérieur” defined by parameters such as blood pressure, temperature, concentration of glucose in blood, and so on, achieved by physiological processes.

2. Basic Concepts

2.1 Foundations

2.1.1 Retroaction

According to the title of Wiener’s most famous book, control and communication play a fundamental role in cybernetics. In this context, control is to be understood mainly as retroactive control, more precisely as negative feedback. As a concept, negative feedback belongs to the twentieth century, but the phenomenon itself can be traced back into antiquity—for example, in the clepsydra water supply, or the regulation of the speed of a mill. In more modern times, Watt’s governor gives an excellent illustration that was carefully studied, from the mathematical point of view, by J.C. Maxwell.

In these regulation problems the purpose is to maintain an essential parameter of a dynamical system at a chosen value. It is a level of water for the clepsydra, a rotation speed for a mill or a steam engine, and a temperature for a thermostat. In the case of the steam engine, when speed rises too high the steam supply is reduced through the classical device of a flywheel acted upon by centrifugal forces. In the general case a comparison is made between the value of the considered parameter and its desired level. The observed gap generates a countermeasure tending to modify the parameter in the desired direction: when the difference is positive it must be decreased, when it is negative it must be increased. The fact that the actual value (output) is compared to the desired value (input) justifies the word feedback, or retroaction. This is said to be negative as it acts to decrease difference between input and output.

In more general cases the purpose of negative feedback is not to maintain (as closely as is possible) the value of a parameter at a chosen level, but to make it follow a given law of evolution despite unforeseen perturbations. In these cases, scalar differential equations give excellent representations of the systems for which criteria of stability have been given. The above considerations may be extended (by generalized negative feedback) to the control of not only a single parameter of a system, but of all the parameters defining its state (see Appendix 1). Results obtained by R. G. Bellman, R. E. Kálmán, and L. S. Pontryagin suggest that perhaps even optimal control (for a given criterion) should be considered.

2.1.2 Information

Aside from control, the other fundamental concept of cybernetics is communication. Communication is closely connected with signal theory—a domain which interested Wiener even before cybernetics. Wiener presented his work in this field in his book on time series, in which he utilizes his previous results on Brownian motion and generalized harmonic analysis. The problem he solves is that of the elimination of noise interfering with a signal, and also of the prediction of future values of this signal. Both elimination and prediction are achieved by the use of a frequency filter set to a given criterion—a solution already foreseen independently by V.A. Kolmogoroff.

Wiener's interest in the study of signals corrupted by noise is justified by the role they play in transmission of data—and more generally, information—from one part of a cybernetic system to another. Claude E. Shannon made a very important advance in this field, considering (as Wiener did) that his purpose should be to study the capacity of a channel to transmit a signal without degradation from noise. The meaning of the signal should not be taken into account—an axiom on which Shannon insisted that, in fact, has not always been heeded.

What Shannon considered was what he called the "quantity of information" attributed to a message represented by a signal. This expression, perhaps unfortunately formulated in some aspects, has no semantic connotation. It is linked to the unexpectedness of the message. More precisely the quantity of information attributed to a message telling that an event, of probability p, has occurred is $I = -\log_2 p$, where $\log_2$ means logarithm with base 2. When p tends to zero I tends to infinity, when $p = 1$ then $I = 0$. So the greater the unexpectedness, the greater of the quantity of information. If $p = 1/2$ then $I = 1$. This means that the unit of quantity of information corresponds to the circumstance where the realization and the non-realization of the event are equiprobable. This unit is called a bit (binary digit), and less frequently a Hartley, in remembrance of R. Hartley who pursued pioneering work in this field at the same time as H. Nyquist.

For Shannon, a communication system may be represented by a source of information providing an input message that is then changed by a transmitter into a signal suitable for transmission over a channel. The output signal results from the addition of noise to the input signal. The output signal enters a receiver, delivering the output message to its destination. For the sake of simplicity we shall now consider the case of a discrete source of information generating an input message constituted by a sequence of symbols that occur according to certain probabilities. The input message is encoded into an input signal—a sequence of other symbols that also occur according to probabilities. This signal is disrupted by discrete noise that is also probabilistic. Shannon has shown that if the average quantity of information produced by the source, per symbol and unit of time, is less than or equal to a certain number C, there is a coding of the input message into the input signal such that the transmission, up to the output message, is realized with a frequency of errors arbitrarily small. Shannon calls C the channel capacity. The average quantity of information considered above needs a precise definition. Let $\{s_1, s_2, \ldots s_n\}$ be the set of symbols from which the source chooses. If p_i is the probability of occurrence of symbol s_i, the quantity of information associated to this occurrence is $-\log_2 p_i$, and the average quantity of information per symbol is

$$J = -\sum_i p_i \log_2 p_i$$

So the average quantity of information considered by Shannon is J/d if d is the mean duration of the emission of a symbol. We may remark that $J = 0$ when one p_i equals 1 (the others equaling 0), and that $J = \log_2 n$ when all p_i are equal to 1/n, these values being the extremes of J.

If we consider a thermodynamical system whose possible n states have probabilities $p_1, p_2, \ldots, p_n$, its entropy is, by definition,

$$E = -k \sum_i p_i \log_e p_i$$

where $\log_e$ means natural logarithm (base e) and K is Boltzmann's constant. Shannon was of course aware of the formal analogy between J and E—which is why he also called the average quantity of information per symbol "entropy". This analogy has been considered significant by L. Szílard, B. Mandelbrot, L. Brillouin, and L. de Broglie. The three first authors proposed explanations of the Maxwell demon paradox (supposed to prove that the second law of thermodynamics, concerning the increase in entropy of a closed system, may be inexact in microscopic physics) based upon a kind of equivalence between J and E which has not yet been properly clarified.

L. de Broglie's interest in cybernetics was mainly due to information theory and its possible implications in theoretical physics. At a time when cybernetics was not accepted by mainstream thinkers in the USA, Europe, or the USSR, he expressed his sympathy for it. It may be remarked that after the death of Stalin, cybernetics—which had previously been considered a bourgeois theory aimed at enslaving the people—became very popular in Russian academic circles.

2.2 Other Important Concepts

2.2.1 Variety

Modern games theory started with E. Borel and reached its present status with J. von Neumann. The first link between games theory and cybernetics—communication—was discovered by B. Mandelbrot. He saw communication as a duel between the transmitter, which "wants" to inform the receptor, and "nature" which passively spoils the signal with noise. Another link may be found in W. Ross Ashby's "principle of requisite variety" (later improved in a special case by R.C. Conant). This principle implies that the greater the capacity of a regulator to transmit information through its feedback loop per unit of time, the better its capacity to successfully resist noise. More generally, to efficiently resist a given level of variety of aggressions, it is necessary to dispose of a comparable level of variety of opposite actions—only variety can destroy variety.

It must be added that W. Ross Ashby's contribution to cybernetics is not limited to requisite variety. He also proposed the idea that every good regulator of a system of must be a model of that system; and built up a cybernetic device he called a homeostat. The homeostat gives a model of how, for example, a physiological system looks for a state of equilibrium and attains it after many intricate behaviors.

2.2.2 Observers

"Second order cybernetics" is an expression introduced by Heinz von Förster, anticipated to a certain extent by some of the material in Wiener's book. It emphasizes the role of the observer as played by a cybernetic device, which has to perceive in order to adjust its behavior to its aims—and so observes both itself and the outside world. This involves a mathematical "observation operator", proposed by R. Vallée, and consequently implies self-reference as considered by von Förster and then by G. Pask, S. Bräten, and L. Löfgren.

The "perceptron" is significant here—a concept able to schematically describe the perceptive properties of an observing system (from the work of Cellérier et al). When some rather general conditions are satisfied, iteration of the process of perception gives rise to a fixed point. This fixed point, which is obtained asymptotically, is invariant under the process of perception considered. It induces, for the observing system, a stable way of acting which von Förster calls "eigen-behavior", an expression already introduced in a different context by N. Jerne. This approach enabled von Förster to interpret, in terms of observation and autopoiesis, Piaget's genetic epistemology—a constructivist view of how an individual builds up his own view of the world. H. Maturana and F. Varela introduced a conception of autonomy and autopoiesis involving "eigen-behaviors" and what they called "operational closure" (see Appendix 2). (See chapter *Second-order Cybernetics*)

2.2.3 Epistemology and Praxiology

By its very definition cybernetics is interested in action, and more precisely with steering, an aspect that is particularly obvious with optimal control. More generally L. Couffignal considered cybernetics as the art of making action efficient. In a paper written with A. Rosenblueth and N. Bigelow, Wiener introduced purpose and teleology into the context of cybernetics. Teleology can be seen to be present each time negative feedback tends to achieve a given purpose. The theory of "ago-antagonism", proposed by E. Bernard-Weil in the context of cybernetics applied to medicine, introduces simultaneous opposite actions in the control of nonlinear systems. Generally, perception is considered independently of decision. Nevertheless cognition and action are intimately linked to each other, and this may lead to an "epistemo-praxiology" (as proposed by R. Vallée) that involves new aspects of subjectivity due to "inverse transfers" of epistemological and praxiological traits of the systems considered.

Teleology has been the origin of many scientific and philosophical disputes. It has been considered incompatible with determinism. Nevertheless it can be argued that a teleological rule is equivalent to a deterministic one. For example the law of refraction, in a medium whose refraction index changes continuously with the point considered, can be expressed in a (deterministic) differential form showing how a ray of light changes continuously its direction. But it can equivalently be presented in a (teleological) integral form, revealing that the line followed by the light is that of shortest time.

2.2.4 Isomorphism and Multidisciplinarity

The title of Wiener's book shows that an important purpose of cybernetics is to find analogies of structure in the animal, the machine, and even societies. The analogies are of mathematical nature, they are expressed by models common to different realizations in the artificial or the natural worlds. These realizations are isomorphisms in the sense that they are perfect images of each other. In fact realizations of mathematical structures are always imperfect, as observed by Plato in his allegory of the cave. But even if the isomorphisms are not perfectly accurate they are very useful in cybernetics as well as in any domain of sciences. In certain cases an imperfect isomorphism is more useful than a perfect one. For example a map is not the territory, as Korzybski noted, and it is all the better for it. The quest for isomorphisms between different domains shows that cybernetics is multidisciplinary by nature.

3. Links with Other Theories

The concept of general systems theory was introduced by L. von Bertalanffy (1901–1972), and was to an extent foreseen by A. Bogdanoff's tectology. Cybernetics, which considers systems as a set of elements in interaction, may be considered a (still distinct) part of systems theory. Synergetics, created by H. Haken, is closely linked to cybernetics and systems, particularly in terms of autopoiesis, control, and information. I. Prigogine's study of nonlinear dissipative structures that are far from equilibrium led him to make important contributions to cybernetics, including insights on irreversible time, another theme which interested Wiener. The idea of "order from noise" proposed by von Förster plays its role in Prigogine's complex statistical systems. However, this "slogan" for the topic must not be taken too literally. It simply means that noise can trigger the emergence of a potential ordered structure, giving rise to autopoiesis. The theory of viable systems, seen from a managerial and cybernetic point of view, has been developed by S. Beer, and—in a purely systemic way—by J. P. Aubin. This has made an important contribution to the understanding of autonomy.

The applications of cybernetics are so numerous and diverse that their common origin is often forgotten even by the people who use them. Robotics and now "artificial life" are obviously indebted to cybernetics. The same can be said of biocybernetics (typified by the work of Y. Cherruault), sociocybernetics (F. Geyer), and cybernetics of ecology. The work of G. Bateson, introducing the notion of "double bind" or contradictory constraints into psychology, was also influenced by cybernetics. Economic cybernetics was started as a subject by O. Lange, and also developed by M. Manescu.

It would perhaps be interesting to reflect upon what is to be understood by the term "general systems theory". When L. von Bertalanffy started to use these words he had in mind what he had previously called "allgemeine Systemlehre"—"a general science of systems". Unfortunately general systems theory has sometimes been understood as referring to "the theory of general systems" instead of "the general theory of systems", due perhaps to its slightly ambiguous phrasing. (See chapter *A Systems Design of the Future*)

4. Future of Cybernetics

In his book Wiener proposed a program which is—even today—still far from completion, particularly in the areas of the nervous system, psychopathology, languages, and society. The world of the artificial offers a favorable domain to work in, but biology, medicine, and human sciences should not be neglected—and have already given results. It seems reasonable to expect some degree of further progress in communication theory, most likely in its semantic aspects. Complexity constitutes quite a challenge to both cybernetics and systems theory, as does the development of a better, more coherent understanding of chaos—a subject that Wiener would have found deeply interesting.

The increasing symbiosis of mankind and the global communications network also promises to provide an interesting area for study, and in particular appears to offer directions for development with consequences that are extremely difficult to anticipate.

Appendix

Appendix 1 – Negative Feedback, Differential and Difference Equations

Some indications have been given about the negative feedback involved in the regulation of the speed of a steam engine. The example of the thermostat may be also of interest. The purpose of this regulator is to maintain the temperature of a place (a refrigerator for example) at a given value. A more general device, acting on temperature, may be devised in order to make the temperature, for example of an oven, follow a given program, as accurately as possible, despite unexpected influences. Let $h(t)$ be the temperature prescribed at instant t and $x(t)$ the temperature realized at the same instant, taking into account a perturbation $p(t)$ which may be a noise. The difference $x(t)-h(t)$ is the gap which is to be maintained, in absolute value, as small as possible. When this gap is positive it must induce an absorption of heat making the gap decrease and conversely when it is negative. A simple representation of this situation is given by the following linear scalar differential equation

$$dx(t)/dt = a\left(x(t)-h(t)\right)+bp(t) \tag{1}$$

With a < o and $bp(t)$ always negligible compared to $a\left(x(t)-h(t)\right.$. Here $h(t)$ and $p(t)$ constitute the input of system: $h(t)$ is chosen purposely, $p(t)$ is an unpredictable perturbation. The output is $x(t)$ which is also the state of the system. When $x(t)-h(t)$ becomes too much positive $dx(t)/dt$ becomes negative, $x(t)$ decreases as well as $x(t)-h(t)$ and conversely when $x(t)-h(t)$ becomes too much negative. We have a negative feedback which makes $x(t)$ not to depart too much from $h(t)$ despite the action of $p(t)$. In more complicated linear cases, conditions more sophisticated than a < o are taken into account such as Nyquist criterion which is based on the theory of functions of a complex variable. Representation by a non-linear differential equation is of course of great interest but leads to great difficulties.

Up to now we have used a mere linear scalar differential equation, the state at instant t of the cybernetical system considered being $x(t)$ which is a number. As already observed, the state $X(t)$ of a system may be defined by more than one number, as well as the perturbing influence $P(t)$ and also the chosen control $H(t)$. Then the corresponding representation, in the differential case, becomes

$$dX(t)/dt - \mathrm{A}\big(X(t) - H(t)\big) + \mathrm{B}P(t) \tag{2}$$

where $X(t)$, $H(t)$, $P(t)$ are column matrices, A a square matrix and B a matrix of adequate format. Here we have a generalized feedback which may be said metaphorically negative if some conditions are satisfied by matrix A.

Another important point about cybernetic systems and their representation is that, in certain cases, time t is not considered "continuous" but "discrete", that is to say taking integer values n. This may be due to the very nature of the system or to a deliberate approximation of the measurement of time. In such a case instead of a linear scalar differential equation we could have a linear scalar difference equation

$$X(n+1) - x(n) = a\big(x(n) - b(n)\big) + bp(n) \tag{3}$$

But instead of a < o we would have a > 1. Of course this may be generalized to the case where we have matrices. It gives then

$$X(n+1) - X(n) = A\big(X(n) - H(n)\big) - BP(n) \tag{4}$$

The properties of these matrix difference equations are in some respects analogous to those of the matrix differential equations but they have also their specificities. The non-linear case is also of interest.

Appendix 2 – Fixed Points and their Interpretations

If f is a mapping of set E on itself, x is said to be a fixed point of f if

$$F(x) = x \tag{1}$$

Element x may be a number, a point, a function …In case of a number, x is a root of equation $f(x) = x$. If x is a vector and f a linear operator, x is an eigen-vector of f with eigen-value 1 (if we had $f(x) = sx$, the eigen-value would be s). Seen from a "dynamical" point of view, x may be considered as the limit of the iteration process, supposed to be convergent,

$$F(x_n) = x_{n+1} \tag{2}$$

giving x_{n+1} when x_n is known, when n tends to infinity. This process generates progressively x and eliminates apparent paradoxes about the "self-reference" implied by $f(x) = x$.

As already said the concept of fixed point enabled H. von Förster to consider a fixed point of an adequate mapping (an operator acting on functions) as a stabilized behavior obtained by an iterative process. Following N. Jerne (1974) he used the term "eigen-behavior" (1976) with a somewhat different meaning. Historically it purposely refers approximately to the term eigen-function, widely used in quantum mechanics, but concerning certain linear operators whose eigen-values are not necessarily equal to I. F. Varela used the term eigen-behavior (1980), adapted from N. Jerne and H. von Förster. It permitted him to present his conception, initiated by H. Maturana (1969), of an "operationally closed" system. That is to say a system whose organization is characterized by processes depending of each other for their own generation and constituting the system as a whole, indentifiable in the space domain where these processes occur. Fixed points may also be found in "epistemo-praxiology", presented above.

Glossary

Autopoiesis:	Also called self-organization, the property of a system to construct itself.
Brownian motion:	Name given to the agitation of small particles in suspension in a liquid, due to molecular movements, as discovered by the botanist R. Brown.
Communication:	The transmission of information.
Control:	Also called steering.
Cybernetics:	The science of steering in its broadest meaning, consequently involving the theory of transmission of information.
Dissipative structure:	A dynamical structure which maintains itself while dissipating and also receiving energy. Such structures have been studied by I. Prigogine in the case of thermodynamical systems far from equilibrium.
Entropy:	A parameter of a thermodynamical system which always increases when the system is closed. It has been interpreted, in statistical mechanics, as the degree of disorder of the system.
Epistemology:	The study of what can be known and how it can be known.
Equilibrium:	A dynamical system is said to be in a state of equilibrium if, not subject to external influences, it stays in the same state.
Feedback:	The output of a system influences its input through feedback. If this influence acts negatively the feedback, which is then said to be negative, tends—under correct conditions—to stabilize the system.
Harmonic analysis:	Representation of a periodic signal by a sum of sinusoidal functions. This can be extended to non periodic signals—Wiener's generalized harmonic analysis concerns probabilistic signals.
Homeostasis:	A system is said to be homeostatic if it is stable. It means that it tends to come back to its equilibrium state despite small perturbations.
Isomorphism:	Two structures are isomorphic if there is a one-to-one correspondence between their elements and, under certain

	conditions, between the relations linking them. The two structures are perfect images of each other.
Noise:	Any signal which is considered uninteresting or disturbing. It is often considered from a probabilistic point of view.
State:	The state of a deterministic system at a given instant is what needs to be known about it to be able, in principle, to predict its future behavior.
Variety:	The variety of a set of n possibilities is generally measured by the logarithm (base 2) of n.

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Biographical Sketch

Vallée (Robert) was born in 1922 in Poitiers (France). His father and mother were professors. He studied at the Lycée d’Angoulême, Ecole polytechnique (Paris), and the Université de Paris. During the course of his career, he has been Associate Director of Institut Blaise Pascal (1956-1958)., Maître de conférences at Ecole nationale supérieure de l’aéronautique (1958-1962) and at Ecole polytechnique (1961-1971), Professor at Université de Besançon (1962-1971), Professor (1971-1987) then Professor emeritus (1987) at Université Paris-Nord., Professor at Université Paris I (1975-1987) and at Université Paris II (1988-1989), Director-General of the Institut de Sciences Mathématiques et Economiques Appliquées (1980-1982)., Editor in Chief of Revue Internationale de Systémique (1986-88), And Director-General and Honorary Fellow of the World Organisation of Systems and Cybernetics (1987–). He is a Member of Société Mathématique de France (member of the council, 1964-1967), Member of the Board of Administration of Association Internationale de Cybernétique, Member of the International Society for the Systems Sciences, Honorary President of the Collège de Systémique de l’AFCET, Vice-President of Cybernetics Academy Odobleja, Member of Académie Francophone d’Ingénieurs, and Member of the Council of AFSCET.

Dr. Vallée has published over 120 articles in international scientific journals on mathematics, cybernetics, and systems. He is the author of *Cognition et Système, essai d'épistémo-praxéologie,* and editor of two books on systems and information applied to economics. He was awarded the Medal of Collège de Systémique de l'AFCET in 1984, the Norbert Wiener Memorial Gold Medal, and the distinction of Dr Honoris Causa of Universitatea din Petrosani in 2000.

EXISTING CYBERNETICS FOUNDATIONS

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Keywords: Cybernetics, system, control, black box, entropy, information theory, mathematical modeling, feedback, homeostasis, hierarchy.

Contents

Summary

Cybernetics is a science that studies systems of any nature that are capable of perceiving, storing, and processing information, as well as of using it for control and regulation.

The second title of the Norbert Wiener's book "Cybernetics" reads "Control and Communication in the Animal and the Machine". However, it is not recognition of the external similarity between the functions of animals and machines that Norbert Wiener is credited with. That had been done well before and can be traced back to La Mettrie and Descartes. Nor is it his contribution that he introduced the notion of feedback; that has been known since the times of the creation of the first irrigation systems in ancient Babylon. His distinctive contribution lies in demonstrating that both animals and machines can be combined into a new, wider class of objects which is characterized by the presence of control systems; furthermore, living organisms, including humans and machines, can be talked about in the same language that is suitable for a description of any teleological (goal-directed) systems. This epistemological assumption has determined to a great extent the specific means and methods that are used in cybernetics.

An analysis of the existing paradigms and views on the subject, and the content of this area of knowledge, shows that the foundations of cybernetics are formed from the principles of organization of complex systems, the processes of information transfer, storage, and processing, and the mechanisms of goal-directed control. It is precisely these principles, processes, and mechanisms that are used in the study of the specific properties of control and communication which provide for the synthesis or simulation of the behavior of living organisms and automatic systems, and that constitute the essence of cybernetic research.

To obtain concrete results, various mathematical methods that allow the construction of effective dynamical models are widely used in cybernetics.

1. Introduction

Cybernetics is a science that studies systems of any nature which are capable of perceiving, storing, and processing information, as well as of using it for control and regulation. This is one of the many definitions of cybernetics. Some others are:

- Cybernetics studies systems that are open with respect to energy, but closed under information and control.
- Cybernetics studies various informable, informing, and information systems.
- Cybernetics studies how to create, reveal the design of, and identically transform algorithms describing control processes.
- Cybernetics studies the optimal, goal-directed control of complex developing systems.

Despite the seemingly apparent differences in these definitions, an analysis of their specific content shows that the difference lies not in the subject itself, but rather in the varying approaches to phenomena under study. It becomes especially clear if we consider the main notions and principles of cybernetics.

The second title of Norbert Wiener’s book “Cybernetics” is “Control and Communication in the Animal and the Machine”. However, cybernetics, as a science, is not credited with placing emphasis on the apparent kinship between human and animal functions. That had been noticed long before cybernetics was born, and dates back to La Mettrie and Descartes. Nor is cybernetics credited with the introduction of the notion of feedback—an adjustment of controlling actions on the basis of information about their results. The idea of feedback itself was known as early as ancient Babylon with its creation of irrigation systems. However, cybernetics has been crucially important in noticing that any feedback system is automatically goal-directed. The difference between an automatically directed system and a system that attempts to reach its goal as a result of will power impulses is purely implicit, “internal”, and cannot be established with certainty by application of any external criterion.

Therefore, the achievement of cybernetics can actually be seen in the demonstration of the fact that both animals and machines fall into a new, wider class of objects that is characterized by the possession of control systems. In other words, cybernetics not only draws analogies between animals and machines, but also studies the questions of system development at such an abstract level that, in context, both animals and machines merely represent special cases that can be approximated by modeling. The significance of cybernetics also lies in that it makes it possible to talk about living organisms, including humans, and machines, in the same language that is equally suitable for a description of any teleological (goal-directed) systems. This last assumption, which is inherently epistemological, has essentially determined the specific means and methods used in cybernetics.

An analysis of the existing views on the subject and content of this area of knowledge shows that the foundations of cybernetics are the principles of complex systems organization; the processes of information transfer, storage and processing; and the mechanisms of goal-directed control. It is precisely these principles, processes, and mechanisms that are used to study the specific properties of control and communication, which provide for a synthesis or simulation of the behavior of living organisms and automatic systems, and that shape the core of cybernetic research.

One of the basic ideas introduced by cybernetics into modern philosophy is a new view on the components of the world around us. The classical notion of the world consisting of matter and energy has been changed to that of a world which has the three components of matter, energy, and information, since an organized system without information is unthinkable.

It has also become apparent that complex systems are not entirely determined by their physical descriptions. Their information content and control structures must be described as well. For example, the "gene" system is not wholly determined by the description of the DNA molecules; the gene also contains the information encoded by the configuration of the molecules as well as by the control chains that synthesize proteins. It is in that context that the gene becomes a unit of heredity.

Another principal question posed by cybernetics is the relationship between the abilities of computers and thinking, which represent extreme types of control systems, fully formalized in case of the computer and not formalized at all in case of human thinking.

As cybernetics developed, the approach to this basic question transformed, and cybernetics and artificial intelligence became separated. In the field of artificial intelligence, models of systems implementing various aspects of knowledge-seeking activities are developed; however, the methods used are not required to be the same as the ones used by humans and animals. On the other hand, in cybernetics we always talk about "resemblance" to live prototypes.

Cybernetics possesses two aspects: syntactic and semantic, if both terms are used as in linguistics. The former is related to the study of the principles that determine how the set of all possible systems functions; the latter is concerned with interrelationships between these principles and actual systems belonging to various knowledge areas. Furthermore, the main emphasis is on the very complex probabilistic self-adjusting systems which are studied in cybernetics.

Research on these systems is conducted at the level of organization and information. The properties of the material from which a system is composed are considered only to the extent that they affect the organization. To obtain specific results, various mathematical methods are used. These methods must enable us to design effective dynamical models; this constitutes the main methodological technique in cybernetic research.

It has become absolutely clear that many of the conceptual schemes that determine the behavior of living organisms when solving specific problems are virtually identical to the schemes that characterize control processes in complex man-made systems.

Furthermore, there is no doubt that both social and economic control models can be analyzed on the basis of the same general assumptions and notions that have been developed in cybernetics.

When studying general rules and laws that are possessed by systems very different in their nature and specific activity mechanisms, it is necessary to apply far-reaching abstraction processes, based on a number of mathematical disciplines such as probability theory, mathematical statistics, set theory, functional analysis, topology, etc. Being based on mathematics, cybernetics in turn propels the development of the mentioned branches of the mathematical sciences and the creation of new ones. As a matter of fact, such areas of mathematics as information theory, game theory, automata theory, and several others were invented and took shape as a direct consequence of research in cybernetics.

2. Organization

Among the core three components—organization, information, and control—organization can be arguably positioned as the most important, since it is the very basis for all the subsequent analyses of cybernetic systems. It was John von Neumann who first emphasized that, when complex systems are studied, the question of how the elements of a system function presents just one part of the problem. The second part is concerned with the way in which these elements are connected to form the whole. It is exactly this part that is properly cybernetic because it is related to system organization, and to the evaluation of the degree of that organization.

2.1 Systems and Complexity

Usually, organization is defined as a set of elements united as a whole in such a way that their various activities are put into a common order that determines the specific properties of the system thereby formed.

In its turn, a system is a set of interacting elements or processes united as a whole by the realization of a common function that is irreducible to a function of the system's components. Hence, the notions of system and organization are closely intertwined.

Some of the system's features are as follows: when interacting with the environment, the system acts as a whole entity; every element of the system cannot be decomposed further; when external conditions and the internal state change, the general structure of interactions among the system's elements remains the same.

The common property, shared by all systems, is the presence of some input variables which are transformed into output variables according to a function realized by the system. The most complete characteristic of any system is a description of the entire set of values of the variables that determine its behavior. Such a set is a state space of the system and consists of the sets of input variables, output variables, internal states, state-to-state transfer functions, and output functions.

As a rule, the state space is n-dimensional where n is the number of independent variables, or, in other words, coordinates. In the state space of a system, the number of independent variables is the number of its degrees of freedom.

The presence of a large number of nontrivially interacting elements leads to the conclusion that, in cybernetic systems, the whole is more than a sum of its components. It is not possible to draw correct inferences about the properties of the system as a whole if only the properties of the components and their interactions are given.

The organization of cybernetic systems also reveals itself in the process of control. For organized systems, it is typical that at each moment of time their dynamics are determined by a relatively small number of parameters. This feature allows one to rationally design the control process, and to seek the most important properties of such systems.

The complexity of cybernetic systems is usually imparted in a hierarchy; all hierarchical systems share common properties that are independent of the specific content of those systems, but are determined by the intensities and the interaction structures of their subsystems.

Therefore, a hierarchical system is defined to be a system consisting of interrelated subsystems, each of which, in its turn, is hierarchical in structure, etc., until some lowest level of the elementary subsystems is reached. Hence, the special property of hierarchical structures is the successive separation of the system into co-directed subsystems.

It is widely recognized that biological systems are hierarchically organized. If the cell is to be considered an elementary subsystem, then cells are organized into tissues; tissues are organized into organs; organs are organized into the systems of organs; the systems of organs are organized into the organism, etc.

The notion of hierarchical organization is closely related to the ideas of organizational levels, i.e. levels of description, abstraction, and decision-making complexity for cybernetic systems. According to these ideas, it only makes sense to study living organisms at levels higher than the chemical and physical ones; furthermore, it is precisely at these levels that principally new phenomena, which are essential to self-organizing systems, but not observable at the lower levels, occur.

In terms of their functional organization, all systems can be classified as either deterministic or probabilistic. A deterministic system is a system that can be studied without any uncertainty. For such a system, if a current state, input signal, and input transformation rules are specified, the next state can be predicted with 100% accuracy. However, if under the same conditions the prediction can only be made with some probability, such a system is called probabilistic. It has been mentioned above that the probability is one of the properties of systems studied in cybernetics.

2.2 Organizability

An essential property of any complex system is the degree of its organization, which depends on how varied the elements and their connections are, as well as on the multiplicity of connections. Hence, the degree of organization is determined by the sufficient structural and functional complexity of the system. Organizability, i.e. the presence of a certain structure that manifests itself in the expediency of the system's elements and their connections, is a necessary condition for the existence in the system of at least potential possibilities for control.

It is difficult to define the notion of organizability, but it seems intuitively conceivable that organized systems possess, to a greater or lesser degree, some ordering, as a measure of which we can accept the degree of deviation of the system from the thermal equilibrium.

It seems reasonable to assume that organization occurs when a relation between two variables depends on the value or state of a third variable. This can be illustrated by the following simplest example ("chassis of the tent"). Let *a* be necessary for *b* and *c*, *b* be necessary for *a* and *c*, and *c* be necessary for *a* and *b*. Any two of those elements cannot exist without the third; therefore, any attempt at building such a system by successive addition of the elements would fail at the very start. In other words, a system of that type can only exist as a whole, where the interaction between any two elements depends on the third one.

One of the special features of an organized system is its ability to extract order to sustain or even increase the degree of its own ordering. This case is of particular interest since it can serve as a justification of the assumption that there is a universal principle that, for example, enables biological systems to increase the degree of their structural and functional ordering in the processes of growth, development, and adaptation to the environment. Cybernetic systems that implement this principle are called self-organizing.

A special property of self-organizing systems is their ability to adapt their behavior in response to changes in the environment in which they function. Such behavior incorporates both a simple feedback adaptation and its more complex analog, adaptation by learning. In the process, two classes of control tasks are performed: control of the internal organization of the system; and functional control.

The term "self-organization" has at least two meanings. The first one refers to the case where we have a system in which all of its parts had initially been independent from each other, but have developed connections in the process of functioning. The second meaning concerns the case where the transition from a "badly-organized" to a "well-organized" system occurs.

In cybernetics, a "good" organization is one that provides, in each specific case, for interaction of the parts of the system to achieve a prescribed state (goal function). However, generally speaking, the notion of "good" organization is relative. For example, the wide variety of functional connections among different areas of the animal brain is good inasmuch as the environment is rich in connections. On the other hand, if the parts of the environment are not very strongly connected (independent), the adaptation will accelerate if the parts of the brain are likewise weakly connected (independent).

Another peculiarity of organized systems is the presence of functionally different, interconnected parts that permit the distinction of the structure and purpose of various elements of the system, and the establishment of the nature of their interaction amongst themselves, and with the environment.

2.3 Black Box

When organization is studied formally, an auxiliary concept of the "black box" is often used. It formalizes the standard research strategy in which a newly studied object is treated as having an unknown internal structure, but is assumed to be able to perceive some set of input signals, generate some set of output signals, and associate the input with the output according to one of a set of admissible rules.

Therefore, a black box is a system that only avails its input and output variables to an external observer; its internal workings remain unknown. It turns out that a series of important conclusions about a system's behavior can be drawn by observing the reactions of the output variables to changes in the input variables. Such an approach opens a possibility for objective study of systems whose internal structure is either unknown or too complex to deduce their behavior from the properties of their constituent parts and the structure of their connections.

To study a black box, it is necessary to study the information streams and choose an algorithm that would transform the input information to match the output state. When using the black box concept, there is a limit on the information that can be obtained. A black box can only be studied up to an isomorphism. In other words, if, based on the given data, it is possible to design a mechanism that fully imitates the behavior of the black box, the problem can be considered solved. However, the generation of a black box analog, i.e., a device isomorphic to the black box, does not mean that we understand the black box completely. It is necessary to keep in mind that any black-box research of a system cannot principally lead to a unilateral conclusion concerning the internal structure of the system because its behavior cannot be distinguished from the behavior of all systems isomorphic to it.

Whenever a relatively simple system corresponds to the properties of a more complex system, i.e., whenever a one-to-one mapping from the simple to the complex exists (but not vice versa), the systems are homomorphic. Therefore, it should be said that actual black boxes can only be homomorphically mapped to models, devices, and algorithms.

It is always possible to decompose any complex system into several black boxes and focus on the study of the organization and functional principles of just one or some of these black boxes; this is precisely what makes the black box concept so meaningful. When studying a black box, the following problems are solved:

- Determination of the inputs and outputs of the system (homomorphic approach).
- Revelation of the information streams (successive trials aimed at the limitation of the variety of the system's responses).

- Disclosure of the information code, i.e., determination of the necessary dichotomies, the rules according to which an input state is mapped onto an output state.
- Design of a model homomorphic to the black box under study.

Advances in the analysis and synthesis of cybernetic systems can be symbolically presented as the replacement of black boxes by white boxes where a white box is understood to be a system that is built from well-known elements that are connected in such a well-known way that the given dependence between the inputs and the outputs is implemented.

The black box concept is, to a certain extent, a realization of the epistemological assumption in cybernetics, which states that any clear (rule-based) description of behavior can be formalized. Hence it is possible, at least in principle, to represent the behavior of a human by a set of independent statements that describe the "inputs" of the organism and are correlated with the statements that describe its "outputs". (See *General Systems Theory*.)

3. Modeling

The mathematical part of cybernetics is the algorithmic description of how control systems function. Apart from formalized mathematical descriptions, an essential role is played in cybernetics by other research methods based on observations, statistical analysis, and especially modeling (machine experiments).

Therefore, the cybernetic approach is not a mere system description by formalism. It is an attempt to conceive how actual systems work by means of designing effective dynamical systems.

Research on simple systems can be conducted within the framework of classical mathematics. However, for complex systems, in particular, biological ones, these methods are usually inapplicable. An effective study of such systems, which consist of a large number of elements with varied, irregular interconnections that cannot be reduced to simple rules, turns out to be impossible in terms of classical deductive methods. Hence, the basic complex-system research method used is mathematical modeling through simulation experiments on computer. Since the middle of the twentieth century, this method of modeling has become a new method for the scientific quest for knowledge. In cybernetics, the concept of modeling has shaped the methodology of research on the behavior of cybernetic systems. The advancement of this research method will essentially determine the success of further developments in cybernetics.

Cybernetic systems are complex probabilistic systems whose internal structure is unavailable to direct observation or experiment. Therefore, when studying any one of these systems, an ideal model analog, consisting of clearly described elements with certain interconnections, is built. The description of the elements and connections uses the fullest available knowledge about the real system, taking into account the rules established previously. Whenever actual knowledge is lacking, hypotheses and postulates concerning the organization principles and control mechanisms of the system under study are used. The description is formulated in a mathematical language, which allows one to derive judgments about some features of the system by applying formal procedures to its description; and also to obtain from the analysis conclusions which are as powerful and rigorous as proofs. Using computer modeling, the behavior of the model in the environment, which is also specified by some model, is revealed.

The results of the model functioning may or may not turn out to resemble the behavior of a real prototype system, which is known from experience or observations. It is precisely this resemblance or discrepancy that permits one to accept, correct, or reject hypotheses and postulates used in the model and, therefore, to obtain some additional knowledge about the structure and control algorithms of the system under study. This is the essence of the modeling method.

Hence, the model being created plays the part of a dynamical set of interconnected hypotheses. Any changes in any part of the model induce changes in many other parts; this behavior corresponds to causal relations in the actual system.

The cornerstone of modeling is the fact that the same behavior can be exhibited by systems that are very different in form, structure, and the nature of their internal processes. Systems characterized by the same sets of input and output variables and whose responses to an external impact are the same are isomorphic. For an observer of the inputs and outputs only, such systems are indistinguishable. Furthermore, the extent to which a mathematical model is isomorphic to the real system determines the reliability of predictions that come from this model.

On the other hand, since a mathematical description cannot be comprehensive and ideally precise, mathematical models describe not the real systems, but rather their simplified (homomorphic) counterparts, and their behavior can only correspond to the behavior of the real system in a limited time interval.

Mathematical modeling and computational experiment are novel methods of cybernetic research, where we are not concerned with a simulation of external appearance, but with the kinship of the functional structure of the objects, and the unity of the processes of communication and control in living and non-living systems. Cybernetic modeling is distinguished by the following properties:

- Wide use of the abstract black box technique, which encompasses multifarious, often very different objects.
- Functional approach to modeling aimed at revealing functional, not structural, similarities.
- Studying models not from the point of view of functional mechanisms, but as control mechanisms.
- Domination of homomorphically reflected mathematical models.
- Wide use of computers.

The design of cybernetic models requires the precise formulation and clear and definite understanding of the interrelations existing in the system under study. However, studying the models created in different ways helps in comprehending the object being modeled and, as a rule, becomes the source of new tasks and study plans. Therefore, cybernetic models are heuristic.

There are several other motives to create and use models in cybernetics. In some cases, processes in real systems are too slow or too fast, which makes actual experiments and observations virtually impossible. In these cases, models substitute for real systems. Such models are easier and more convenient to work with, and many results obtained with them are applicable and useful in understanding real systems; live ones, in particular.

After a complex system has been studied and modeled in enough detail, and the underlying principles of its organization and control have become clear, the model can be used to exhibit those principles.

Finally, sufficiently advanced machine-experimental models of cybernetic systems can be used as prototypes of software or hardware packages capable of solving the specific applied problems more effectively. (See *Metamodelling*.)

4. Information

Control is essentially the process of receiving, storing, transforming, and communicating information; hence information, together with the notion of organization, is one of the fundamental notions of cybernetics. It enables one to consider very different processes from a unified point of view.

4.1 Notion of Information

Information is a message about events occurring in a complex system and the environment. Such information is sent via communication channels (physically as different as air, water, metal conductors, etc.) which implement interactions among the elements of the system or between the system and an external source of information.

The ideas that became widespread as cybernetics developed propelled the use of the word “information” in the situations in which it had not been used before, e.g., to establish a communication between humans and animals; among animals; among machines; in the context of inheriting features, etc.

What is sent via communication channels is a flow of matter or energy, but that flow always includes a certain element of choice, the choice of that particular flow type among all realizable types. This choice is information, and the flow of information can be considered independently of the specific physical carrier processes.

Information is sent by means of signals that are physical processes which can exist in various forms: electrical, acoustic, chemical, etc. Signals can be passed over a distance, thereby providing communication among objects in space, or can be stored for subsequent transfer, thus providing communication among temporally separated objects.

The parameters of the physical processes which are used for information transfer must bijectively correspond to the information being transferred. Establishing such a correspondence is called coding, and the rule used in this process is termed a code.

It is of great interest to study the natural ways of hereditary information coding that preserve, in a minute volume of genetic matter, a colossal quantity of information; which, even as early as in a fetus cell, contains the structure of the organism and the laws of its development.

4.2 Generalized Communication System

The structure of a generalized communication system includes the five parts:

- Information source, which selects one message out of all messages to be transferred.
- Transmitter, which codes the message and generates signals that carry that coded message over the communication channel.
- Communication channel, which is an environment in which information transfer from the transmitter to the receiver takes place. The communication channel is affected by noise sources, and so a signal distortion is possible in the process of signal transfer.
- Receiver, which decodes the received signal into the original message.
- Information recipient, which is a living organism or a device for which the message was intended.

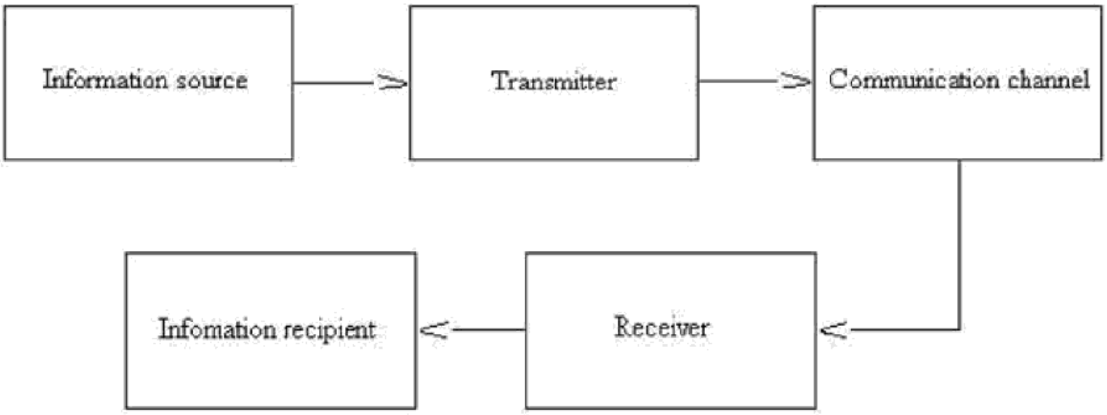

Figure 1. Block chart of a generalized communication system.

Mathematically, an information source is defined by a set of possible messages that it can generate, together with the probabilities of their occurrence. Those messages are not transmitted directly, but rather first put into a coding device, which allows the messages to be transmitted.

A communication channel is mathematically defined by a set of messages which it can receive, a set of messages it can transmit through itself, and a matrix of conditional probabilities of occurrence of every output message as a result of every input message. The process of information transfer is an information flow that is related to the notion of information quantity, which does not depend on the semantic (meaning-wise) content.

As an example of a generalized communication system, let us consider the following system:

Book → Eyes → Neural pathways → Subcortical visual centers → Cerebral cortex

The text in the book represents the information to be transmitted. The eyes are sensual elements that transform the information into signals that can be transmitted over the neural pathways. Subcortical visual centers play the part of the information receiver in this case. They decode the signal to restore the original message. The information consumer (recipient) is the cerebral cortex. If, while the person is reading the book, additional visual stimuli occur, e.g., the luminance of the book's pages changes, distortion occurs and the recovery of the message becomes more problematic.

Another example of a noisy channel is the animal or human reproductive system, via which hereditary information is transmitted in DNA molecules. Fields of various nature present noise, which can sometimes distort the signals being transmitted. This can have obvious undesirable consequences.

The use of information for control purposes necessitates its quantitative estimates. These are studied in information theory, which is essentially a theory of signal transmission via communication channels.

To estimate information quantitatively, it is necessary to diverge from the signal content and consider it abstractly. Cybernetics deals with information without regard to the nature of its source. The media can be light, sound, a letter, digit, etc. However, the laws of information transfer, reception, and processing are the same for all types of cybernetic systems. It is precisely that which makes cybernetics a synthetic science.

4.3 Information Theory

The rigorous notion of information, or, more precisely, information quantity, was only "naturalized" in the 1950s, despite the fact that the word itself (Latin *informatio*—clarification, narration) has been known for a very long time. It has been used for a long time to denote some particulars and the process of their transfer and reception.

The needs of communication theory had led to the development of a complex set of ideas that have eventually shaped information theory. Modern information theory is a scientific discipline that studies the most reliable and cost-conscious ways to transmit and store information. However, being a division of mathematics and cybernetics, information theory is widely used to solve a variety of problems in many different areas of knowledge.
The creator of this scientific discipline was Claude E. Shannon who published the work "Mathematical theory of communication" in 1948, which laid the foundations of information theory. For the sake of fairness, it should be noted that the ideas that formed modern information theory had occurred long before that work went to print.

The idea of a connection between probability and information had been pronounced by the well-known English statistician, Sir Ronald Fisher. A series of results that played a significant role in forming information theory were formulated in physics as early as the nineteenth century. In particular, the fundamental work of Ludwig von Boltzmann made it possible to relate the notions of probability to the measure of irreversibility (indefiniteness) of thermal processes, termed thermodynamic entropy. Later on, the notion of entropy, applied to signal transmission processes, was reconciled with the notion of information quantity—an event fundamental to information theory.

Information theory does not define the notion of information itself. However, the necessary and sufficient condition for this theory to be built is information quantity. Information quantity must be defined by means of something that is inherent in the whole variety of existing information, while remaining insensitive to the meaning and value of the information. This common property is the fact of conducting an experiment (trial), understood in the broad sense, and the presence of uncertainty in the outcome of the experiment. In fact, if the recipient had known before the experiment what message would be received in the end, then, having received the message, the recipient would not have obtained any information quantity.

It is also clear that after an experiment has been conducted the situation becomes more definite, since it is then either possible to unilaterally answer the question posed before the experiment, or to decrease the number of possible answers, and consequently the uncertainty. The amount of decrease in uncertainty can be considered the information quantity obtained in the experiment.

Hence, a measure of information quantity (I) must possess the following intuitive properties:

- Information quantity obtained is greater in a trial that has a greater number of possible outcomes.
- A one-outcome trial, i.e. when an event occurs with probability 1, carries zero information quantity.
- Information quantity in two independent trials must equal the sum of the information quantities in each.

The only function on the domain of possible outcomes that satisfies those requirements is the logarithm function.

It is understandable that the maximum information quantity that a message can contain must be proportional to its length, so $I_{\max} \approx \log N$. The choice of the coefficient of proportionality can be reduced to the choice of the logarithm base and determines the choice of the unit of information quantity. In information theory, the logarithm is chosen to be of base 2. In this case, the information quantity in the choice of two possible messages is taken to be the unit of information quantity and is called “bit” (from BInary digiT).

A measure of the maximum information quantity that a message can contain was introduced by R. V. L. Hartley in 1928. This measure possesses two important properties:

- It is monotone increasing with respect to N and
- It is additive.

The additivity property reflects our intuitive consideration that the information quantity in two independent messages is equal to the sum of the information quantities in each of them.

The quantity proposed by Hartley indicates the upper bound for information quantity that a message can contain. The actual information quantity depends not only on the number of possible messages, but also on their probabilities. This was taken into account by C. Shannon in the measure of information quantity that he developed.

If the message x_i has the probability of occurrence p_i ($i = 1,2,\ldots,n$) and

$$\sum_{i=1}^{n} p_i = 1,$$

then the information quantity is given by Shannon's Formula: $H = I = -\sum p_i \log p_i$

This formula determines the information quantity provided there is no uncertainty after the message has been received. In case some uncertainty remains, a new notion, called entropy, is introduced.

Entropy, traditionally denoted by $H(X)$, is defined to be the average amount of uncertainty in an outcome, before the experiment has been conducted. According to this definition, the information quantity in a message is a measure of removed uncertainty, i.e. it is equal to the information quantity obtained in that experiment.

Entropy can be construed as the information that objects contain about themselves; hence, the maximum information quantity that can be obtained about an object is numerically equal to the entropy.

Entropy is nonnegative, i.e., $H(X) \geq 0$; furthermore, equality occurs if and only if the trial has one possible outcome whose probability is one.

For a given n, the maximum entropy (which occurs when all the outcomes of an experiment are equally likely) is log n.

The properties of entropy described above are in close agreement with the intuitive requirements that a numerical measure of uncertainty must satisfy. It is natural because the postulates above concerning information quantity that can be obtained as a result of probabilistic experiments have been included in the definition of entropy.

When coding information, the character set and probability distribution might change. Therefore, every code for information transfer must be evaluated in terms of the value of relative entropy, which is the ratio of the given code entropy to the maximum possible entropy, i.e. $H/H_{\max}$. Since the maximum value of relative entropy is 1, it is possible to introduce the notion of redundancy:

$$R = 1 - \frac{H}{H_{\max}}.$$

It can also be used to measure how ordered cybernetic systems are.

Before a signal has been transmitted via a communication channel, the entropy H(x) of the message source might be known. After the signal has been received, the information recipient entropy becomes known. Since the received signal is usually distorted by noise in the communication channel, there is also a residual uncertainty characterized by the conditional entropy H(x/y). Using those notions, it is possible to compute the rate of entropy decrease per unit time when a signal is sent via communication channel. The variable $V = H(x) - H(x/y)$ is called the speed of information transfer.

A decrease in the uncertainty of choice, after a signal has been received, with respect to the original signal entropy is called negative entropy (negentropy).

N. Wiener considered negentropy (also regarded as the amount of matter or energy) a fundamental characteristic of natural events. That is why cybernetics is sometimes interpreted as a theory of organization and a fight against any increase in entropy, i.e. information-distorting chaos.

The speed of information transfer via communication channels depends on the probability distributions of both messages and noise. So, messages being transmitted can be distorted not only by a possible noise in the communication channel, but also by the wrong choice of information transmission rate (speed).

The information transmission speed turns out to be maximal for one of such distributions. This maximum speed is called the bandwidth of the channel. Being a salient property of the communication channel, it means that, provided correct coding is used (i.e. the source and the channel are statistically in agreement), it is possible to transmit an information quantity equal to the bandwidth in unit time with an arbitrarily small probability of error.

Therefore, information theory determines how many bits per second can be transmitted via ideal and non-ideal communication channels (depending on their properties); how to measure the speed with which the source generates information; how the message being sent can be coded more effectively; and how transmission errors can be avoided (see *Entropy Systems Theory*.)

4.4 Principle of Necessary Variety

On the basis of information-theoretical notions, the cybernetic theory of biological homeostasis was formulated. In doing this, the following theorem by C. Shannon was used:

Let there be a communication channel fed by some information source. If $H(x)$ is the input entropy, $H(y)$ is the output entropy, and $H(y/x)$ is the conditional entropy, i.e. the uncertainty in the output signal if an input signal is given, then $H(x,y)=H(x)+H(y/x)$. In other words, if the input is known, the joint uncertainty of the system's input and output is equal to the sum of the input and output entropies. To guarantee errorless information transfer via the communication channel, it is necessary to correct the information being received. If the bandwidth of a correction channel is $H(y/x)$, then the correcting data can be coded in such a way that, when sent via the channel, all errors will be corrected. $H(y/x)$, hence, is the amount of additional information that must be transmitted to correct the received message.

On the basis of this theorem, the following propositions were formulated. Any living organism is continuously "shelled" by information originating in the environment and attempting to bring it beyond the limits of survival. Therefore, to reach and maintain stability, the organism must, according to the theorem above, have a supply of information in some "regulating device" (which is analogous to the correction channel) whose volume is at least sufficient to counteract the number of "violations".

(The supply of information is also necessary to provide communication among temporally separated systems. That is why a communication channel must have some "reservoirs" where the information could be stored between the moment of message generation and moments at which it might be used. The existence of those reservoirs is an obvious consequence of the presence of memory in humans and animals.)

This principle of necessary variety, formulated by W. Ross Ashby, means that an organism must constantly accumulate information (against the gradient of the Second Law of Thermodynamics). The amount of the information must be enough for the organism to counteract certain threatening environmental influences.

It is clear that this formulated principle remains true for all levels of organization of life, because metabolism exists at all the levels; the Second Law of Thermodynamics is applicable and similar homeostasis problems exist.

As a conclusion, it can be noted that within the framework of the existing information theory, information like "heads" or "tails" obtained as a result of a coin toss, and information about the result of any other trial with equally likely outcomes (the birth of a boy or a girl) are equivalent.

Therefore, a somewhat blind situation arises, since a whole range of questions related to the meaningful and pragmatic aspects of information processing, naturally, remain unsolved. It follows, then, that it would be desirable to have and use a broader definition of information in cases when the information transfer circuit includes living organisms, especially for interactions among humans.

According to Warren Weaver, there are at least three information levels and thus three types of problems:

- Syntactic (how accurately the symbols can be sent).
- Semantic (how precisely the symbols convey the meaning).
- Pragmatic (how effective the received values are).

Correspondingly, apart from the statistical approach, information theory also entails a semantic approach that is aimed at developing quantitative methods for the estimation of the meaning and value of information (messages). This field also involves the study of the automatic generation of notions, their classification, and image recognition on the basis of learning and self-learning.

The viewpoint of James J. Gibson should be noted as well. He postulated the necessity of a principally different definition of and, respectively, a different theory of information whenever perception and action organization-related processes in animals and humans are concerned.

Regardless to how relevant such a viewpoint is, any application of information theory methods to natural everyday behavior requires great carefulness. Even greater care should be exercised when applying information-theoretical methods to the analysis of non-conscious activity at the physiological, cellular, or biochemical levels. However, if due care is taken, cybernetics in general and information theory, in particular, can be interesting and promising tools for cybernetic research in biology.

5. Control

The notion of a control system is basic in cybernetics. Such systems are ordered entities of interrelated elements, interacting amongst themselves, and with the environment. These connections and interactions, which form the material basis of control, are due to forces, energy, matter, and information flows. However, cybernetics studies the information side of control processes, diverging from the physical and design characteristics of real control systems.

5.1 Essence of Control

Most generally, control is understood to be an impact of some elements of the system on the others, which brings the system to a prescribed state and enables it to reach certain goals or results.

Cybernetics considers not general systems, but rather control systems. Any control implies reaching some goals by affecting connections among objects. The notion of control goal in cybernetics is quite broad, including the natural expediency of control systems in living nature that is aimed at providing the stability of biological species, and their adaptation to changes in the environment.

Expediency can only be provided if control is present. The essence of the control principle is that the motion and action of large masses, or transfer and transformation of large amounts of energy, are directed and managed by small amounts of energy carrying the information. This principle is the cornerstone of organization and action of all controllable systems, whether automatic machines or living organisms.

So control can be considered as a goal-directed influence on a functioning object that moves the object from one state to another according to the goal, a control task produced within the system itself or imposed from outside. The purpose of cybernetics is to study the common grounds of control in different environments, conditions, and events.

5.2 Structure and Functions of a Control System

Any control system can be separated into controlling part, part being controlled, and communication lines between them. Communication between systems is conducted by signals that represent a physical process carrying control information. The purpose of any controlling system (regulator) is to generate controlling influences for the system being controlled, which, according to the signals being received, makes a transition from one state to another. A regulator is a device that processes information being obtained from outside objects and from within—from the control object via the feedback line (see Figure 2).

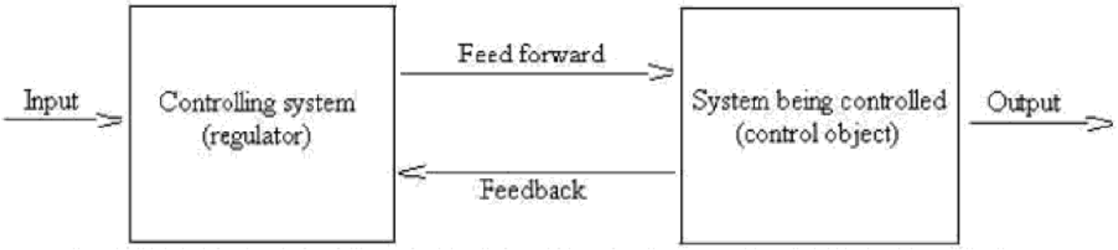

Figure 2. Generalized block chart of information flows in a control system.

More formally, the constituent parts of a control system can be defined as follows:

A system being controlled (control object) is a system in which the changes desired are induced by an action of another system. A controlling system (regulator) is a system whose action leads to the desired change in the other system. A control chain is a system whereby one system affects the other. A control circuit is a feedback circuit that consists of the controlling system, the system being controlled, and the control chains. A control process consists of events in the control circuit.

So all control processes are characterized by the presence of an organized system consisting of controlling organs, and organs being controlled; by an interaction of this organized system with the environment, which produces random or regular perturbations; by the conveyance of control on the basis of receiving and transmitting information; and by the presence of a control goal and control algorithm.

A control algorithm (derived from the name of the Middle Ages mathematician al-Chorezmi who specified a series of rules to perform arithmetic operations) is a set of statements that determine the character and sequence of controlling actions. Control, therefore, is understood to be a process of conducting actions according to an algorithm.

The algorithmic description of control processes and system design is general, and is presented in terms of verbal rules, schemes, mathematical formulas, and computer programs.

The similarity of the general control laws permits one to draw a series of analogies between control systems in living organisms and technical devices. Cybernetics does not emphasize the physical, chemical, or biological nature of control. Physiological processes in the neural cells of the brain do not exhaust the essence of thinking; likewise, electric current in a technical system does not represent the whole complexity of its operation. To master the general control laws, it is necessary to abstract from the specific nature of control elements.

Studying biological control systems, which have perhaps evolved to a state of perfection, provides a possibility to discover new principles for the creation of complex technical devices. In turn, technical and technological advancement allows one to get closer to the study of natural phenomena; to understand the principles on the basis of which living organisms gather, store, transfer and process information; to control different parts of the biological system.

In any complex system, control is implemented at different levels. Furthermore, each level has its own local goals that must adhere to the goal function of the system as a whole. For example, the control systems of some living organisms realize control processes to obtain two types of useful results. The goals of one type are oriented towards the preservation of the species to which the given organism belongs (hereditary material generation, special forms of behavior, etc.—this is the species' system goal). The results of the second type are directed towards the survival and normal functioning of the organism itself (gathering food, oxygen, etc.—the local goal of the subsystem).

If regulating actions are produced by a specially separated distinct element, then the control is called external. Otherwise, if such an element cannot be isolated and the useful result is generated by interaction of the system's elements, then the control is called internal.

In technical or biological systems, there are specialized organs for each control stage: sensors (receptors) that perceive the state of the system itself and environmental factors; a decision-making part (the central nervous system) that evaluates the situation on the basis of the current and previously available information and makes a decision concerning behavior necessary control actions, and executive organs (effectors, e.g. muscles) that form control signals and directly affect the object being controlled.

5.3 Feedback and Homeostasis

Control is based upon the transfer of various information signals inside the system. Any chain of elements by which signal transfer is conducted can be considered an information transfer channel. These channels form feed forward and feedback connections in the system. A feed forward connection takes place if the signals are sent in the forward direction, from the system's inputs to its output, i.e., from the beginning of a chain to its end. An example of such a feed forward chain is the chain of signal transfer when one pulls away a hand from a hot surface.

The feedback principle is of crucial importance in cybernetics. Along with the hierarchy principle, it is the foundation on which all cybernetic control systems are built. Together, these principles provide not only the stability, but also the adaptability of control systems to changing conditions and, in particular, are the bases of the evolution of biological species.

The general structure of the feedback control process is intrinsic to systems of various physical nature, including the organic world, from the early stages of biological evolution to the launch of spaceships by man. On the basis of feedbacks, the behavior of complex systems assumes integrity, ordering, and expediency. N. Wiener characterized feedback as the property that allows regulation of future behavior by obedience to orders in the past. Taking into account the differences between an action and its result is the ultimate essence of feedback mechanisms, which are absolutely necessary to balance a complex probabilistic system with dynamical environmental conditions.

It is of principal importance that any feedback system is automatically goal-directed, and that the difference between an automatically directed system, and a system directed by will is purely “internal” and cannot be detected with confidence by any external criterion.

A feedback can be positive or negative. A negative feedback provides the object being controlled with a set of commands from the control device which are aimed at eliminating the difference between the actions of the system and a given program. For example, an increase in body temperature in a living organism leads to a dilation of skin capillaries, which increases heat output. A temperature increase in the thermostat leads to a decrease in heat output, and to a lower heat production. In both cases, despite the principal difference in the mechanisms and details of regulation, the result of the feedback action is the same.

A positive feedback usually strengthens, rather than weakens, the difference. An example of the emergence of positive feedback in the human organism is the epileptic bout, when a small excitation of a cortex area drives a sharp increase in the excitability of other cortex areas, which leads to the excitation of sensory and motor spheres.

The notion of feedback has become quite common. Arguments about positive and negative feedback have almost become generic whenever complex systems of any nature are considered. Therefore, it makes sense to draw attention to the flaws of these two kinds of communication. The notions themselves were introduced for relatively simple one-circuit control systems (i.e. systems that have one feed forward and one feedback channel only).

It is often written that a negative feedback always stabilizes the system, whereas a positive one destabilizes. Both stereotypes are not true. In fact, if it takes a long time for a signal to travel via a negative feedback, that feedback can violate the stability of the system. On the other hand, a positive feedback can sometimes increase the system’s sensitivity to changes in the input signal, without affecting the stability.

One of the main peculiarities of cybernetics is that it considers controllable systems not statically, but instead in their motion and development. For example, stability, which is decisive for evaluations of workability and the possibility of prolonged existence, cannot be considered separately from the dynamics of processes inside the system.

In cybernetics a special role is played by studies of biological systems, since they exhibit an exceptional effectiveness, exceeding the effectiveness of all non-living systems, including man-made ones. This effectiveness is related to the speed of reactions, consolidation of information, and ability to draw sufficiently reliable conclusions based on a very limited volume of information.

A remarkable property of natural biological control mechanisms is their implementation of the homeostatic principle. Homeostasis is different from usual technical regulation in that it realizes the self-regulation principle.

The term “homeostasis” was introduced by Walter Cannon in 1928 to advance the idea of the constancy of an organism’s internal medium. In its modern meaning, homeostasis is the process of the dynamical balancing of a system with the environment. This is a key notion in cybernetics whenever the principal peculiarities of control in cybernetic systems are considered.

Homeostasis, a relative constancy of the internal medium variables under internal and external perturbations, is an important factor in fulfilling the vital needs of an organism. As is the case for any control mechanism, a certain energy expense is required to maintain homeostasis. Therefore, the area of life processes encompassed by homeostasis is limited. Internal medium constancy is preserved wherever additional energy costs are either absolutely necessary for survival (keeping temperature within given bounds), or offer dramatic benefits (regulation of blood pressure).

An organism’s homeostasis strengthens the chances of survival for the organism as a whole. However, the loss of homeostatic properties by some systems will not be deadly for the organism, though living under extreme conditions does become more dangerous. To preserve the organism as a whole, the homeostatic systems might deprive some body parts of the ability to satisfy their needs.

Biological homeostats are control devices that are intended to maintain a variable, such as blood temperature, regulation of insect population size, etc., within given bounds.

In a homeostat, the variable being controlled is maintained at the required level due to a self-regulation mechanism. It does not follow, however, that this level is constant. In general, apart from some world constants, all quantities in nature are characterized by certain variability. But for biological regulating systems, the most important property is that those changes are maintained in the permissible range, determined by evolution. This means that a system possesses a mechanism that returns the variable being regulated to a permissible average level.

There is a multitude of analogies between ideas in the special areas of the life sciences and the fundamental notions of cybernetics. For example, anthropologists admit that social homeostasis depends on symbolically expressed regulation programs, which exhibit themselves in rituals, customs, and traditions. In ethology, the principal task is to study behavior as a means of communication and control; therefore, cybernetic notions play a significant part in that science as well. The same notions of homeostasis, control, and communication have been applied and been proven to be effective when considering a whole range of problems in embryology, population genetics, and the processes of growth and development. It is necessary, though, to consider C. Shannon's opinion, voiced with respect to imperfect use of the notions and methods of information theory in other disciplines. He believed that many notions of information theory may turn out to be very useful in other sciences (such as psychology, economics, and other social sciences). However, the application of information theory to other areas, he stated, cannot be reduced to a trivial transfer of terms from one area of science to another. This quest should be conducted as a long process of proposing new hypotheses and testing them experimentally.

The first model of a technical device to simulate the adaptation properties of living organisms was R. Ashby's homeostat. To conduct a goal-directed search, the homeostat must receive information about the effectiveness of its behavior, i.e. about stability. It "performs" a series of experiments and extracts the data it needs to improve its behavior from them; thus, it acts like a conscious creature studying itself and the world around it and learning lessons that determine its behavior.

The homeostat represents a device in which the combination of feedback and hierarchy principles produces the "ultrastability" property. A control system is said to be ultrastable if it possesses an ability to automatically find the optimal position under any unforeseen changes in the environment, as well as under changes in its internal structure and parameter values. The homeostat is also an example of a device that realizes the principle of necessary variety—the number of degrees of freedom of a regulator is at least as great as the number of degrees of freedom of the object being regulated. It shows that simple systems do not possess enough variety to handle the variety of the environment. Only a regulating device that possesses enough variety itself can be capable of counteracting the variety of the system being controlled.

Another example of the use of certain general principles, revealed through cybernetic research, in control is the black box concept. This concept paves the way for practical mastering of a promising method of controlling an immense variety of complex systems. The point is that the most effective way to find the element needed among a very large number of possible choices is the one that produces the maximum entropy at each choice step. This is the dichotomy method, the method of successive divisions into two parts. In this way it becomes possible to determine the sets of input transformations with respect to which the output states are invariant.

So the control task reduces to the correct choice of controlling "box", with the correct choice of entropy of the system being controlled. The presence of such an isomorphism is one of the requirements that control must satisfy. (See *Bipolar Feedback*.)

6. Conclusions

Organization, information, and control comprise an inseparable unity in cybernetic systems, and so each of those notions is somehow used when discussing the other two. For instance, the degree of a system's complexity is measured by its variety, which in turn is estimated by the number of discernible elements in the system. Cybernetic systems are machines for information processing. As soon as a machine begins to work, some order emerges in it, and it starts to eliminate the initial uncertainty. The emergence of ordering, which is equivalent to the emergence of information, is precisely the important salient property that permits the control of cybernetic systems. Information eliminates variety, and lowering variety is one of the basic methods of regulation. It does not happen because the system being controlled becomes simpler, but because the behavior of the system becomes more predictable.

On the other hand, the nature and volume of control pertinent to a given system reveal themselves in the behavior of the system's internal connections. The state of the connections at each moment of time, in turn reflects the information quantity contained in the system. The structure of the connections and the character of the information flowing to one of the system's elements through them, determine at each moment of time whether the given element is in a prescribed state or not.

Concluding this treatment of the basic notions of cybernetics, and the possibilities which it provides for the study of complex systems, it is necessary to highlight the fact that cybernetics has introduced a wide range of absolutely novel ideas and notions into the world's modern scientific view. Cybernetics has become an inalienable element of our life and the cybernetized world around us. Its consequences create the situation we live in.

It seems likely that in the years ahead, the understanding and use of cybernetics in planning the life, and solving the problems, of human society will increase. Nonetheless, the position of cybernetics today can be compared to the position occupied by infinitesimal quantities analysis in the first hundred years after it was introduced into mathematics. Accusations of mysticism should be put aside and the call of D'Alembert should be heeded: "Allez en avant"—"Boldly go ahead!"

Glossary

Black box:	An object under study whose internal workings are unimportant or unknown.
Control:	A set of actions aimed at sustaining or improving a control object's functioning according to a control goal.
Cybernetics:	A science that studies the general laws of control and information transfer processes in machines, living organisms, and their unions.
Entropy:	A measure of uncertainty of a situation (random variable) with a finite or countable number of states.
Feedback:	The effect of a system's output quantity on the system's input. Or, more broadly, the effect of the results of a system's functioning on the character of this functioning.

$H(x)$:	The entropy of the signal x.
$H(x\|y)$:	The conditional probability of the signal x at the system's input after the signal y has been received at the output.
Hierarchy:	The organization and control principle that presumes that the constituent parts or a sequence of controlling signals are in order, from the highest to the lowest.
Homeostasis:	The ability of living systems to maintain their survival-critical parameters within evolutionarily specified bounds.
Information quantity (I) :	A measure of decrease in uncertainty of a situation (trial with several outcomes).
Information theory:	A branch of science that is devoted to the problems of gathering, storing, processing, and transmitting information.
Information transmission rate (V) :	The average number of information units per unit time.
Information unit (bit) :	An information quantity unit arising when a choice of one of two equiprobable outcomes is made.
Mathematical modeling:	A method of studying processes and events by means of special models. It is based on the identity of the form of the equations, and the one-to-one correspondence between variables in the original and model equations.
$P(x)$:	The probability of the event x.
Redundancy (R) :	The quantity that characterizes the possibility of presenting a message in a more economical form.
System:	A set of interrelated elements, each of which is directly or indirectly connected to all the others.

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